Accuracy Control Risk Management for Modular Submarine Hull Construction

by

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B.S., Engineering
University of Illinois, Urbana-Champaign, 1988

Submitted to the Departments of Ocean Engineering and Mechanical Engineering in Partial Fulfillment of the Requirements for the Degrees of

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Abstract:

Modern submarine production, specifically hull fabrication, consists of numerous processes with inherent variations. These variations stem from such areas as: manufacturing methods, alignment techniques and datum control, material properties, measurement methods, cutting and forming practices, and others. Each process adds a level of complexity and variation to the end product. The current method of production uses lessons and knowledge from past experience to arrive at an acceptable finished hull section, ring cylinder, or related subsection. This practice requires significant resources (labor, time, and material) and may not be an optimal methodology. A better understanding of the existing process, via a systematic critical understanding of current practices and the identification of those Key Characteristics (KC) proven to be essential to high quality, may enable process improvement efforts and a favorable return on investment (ROI). These positive results can only result after gaining a thorough understanding of in-place practices and comparison with industry experience and "best practices."

The ultimate use of this effort is founded in the KC methodology presented. This technique can be readily applied to other manufacturing processes within the submarine fabrication setting as well as other ship and industrial settings.

Thesis Supervisor: Anna Thornton
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This thesis was not an individual effort. I had the support of friends and colleagues—both old ones and the new ones I met as part of the research.

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Special recognition and gratitude is extended to the true craftsmen at Electric Boat Corporation's Quonset Point facility. The shop floor efforts of Mike Belknap and Roger Ball taught me how a submarine hull is manufactured. There is no other way to experience this marvel of engineering. Rad Zelin and the team of Optical Tool professionals also made this research possible.

Thank you Rick Nelson for bring an idea to MIT that allowed me to conduct a thesis involving real world submarine manufacturing issues. Your support and opening the doors for data access will benefit your company, MIT, and the Navy.

I appreciated the fascinating tour and engaging discussion of Boeing's 777 and 767 manufacturing facilities and the time of Bill Greene and Kevin Puzey.

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Table of Contents

List of Figures

List of Tables

1.0 Introduction to Variation Risk Management

1.1 Motivation

Within the manufacturing and production world of product development, variation is the double-edged sword that is simultaneously a problem and an opportunity. Variation Risk Management (VRM) is the engineering and business discipline of accounting for and systematically reducing variation in products. VRM requires an understanding of product design, manufacturing capability, impact of interference, and cost structure for labor content, fixturing, and rework. This understanding must be comprehensive in nature and raises several relevant questions for any given firm.

> What is *variation*?
> How does such *variation* impact my organization's processes?
> What can be done to control the risk associated with *variation?*
> Can the *variation* be substantially reduced?

The difficulty in gaining the fundamental understanding necessary to answer these questions lies in the realization that most organizations do not have a clearly defined and consistent means to control variation from basic product concept, through design, and onto manufacturing.

The research presented here will attempt to contribute answers to two of these questions: 1) the impact of variation on an existing set of manufacturing capabilities; and 2) controlling the risk associated with variation. The major effort involves detailed research of the manufacturing experience and processes at Electric Boat Corporation's Quonset Point (QP) facility. Specifically, the efforts investigated cover

the submarine hull manufacturing portion of QP's activities—the Automated Cylinder Fabrication (ACF) processes. These processes include: transforming raw plate steel into circular frames and curved shell plates, then progressing through the fabrication process to ring stiffened cylinder rings and finally into complete hull sections ready for outfitting of equipment and further assembly.

1.2 Background

The concern over variation control is pervasive within the manufacturing world. In its most basic form, the variation encountered in the process of manufacturing a given product has an immediate and deleterious effect on overall quality. This impact has been widely accepted in response to work by Deming [Deming 1986], Taguchi [Taguchi 1993], and others.

As system complexity increases, the potential impact from variation can be magnified, particularly as more steps and datum transfers occur during the manufacturing process [Thornton, *et al.* 1996]. Gone are the days when rework on final products was the accepted norm prior to shipment. In the face of ever more competition and complexity, companies are finding that they need to better communicate the variation risk along with nominal dimensions from the design phase through manufacturing [Thornton, *et al.* 1996]. Such communication and control attempt to alleviate the costly rework requirements that have long been the accepted *solution* for out of control processes. The clear importance of variation control is, however, overshadowed with the lack of commonly accepted tools or practices to adequately control this variation [Jay 1998]. Thus there exists an obvious need in the literature to understand the impact of and, perhaps more importantly, the control of variation in the manufacture of complex systems.

1.3 Problem Statement

An example of a complex manufactured system is a modern U.S. Navy submarine. The current generation of nuclear submarines are as complex as any engineering system heretofore conceived by man. As such they are subject to every form of challenge from the macroscopic (e.g., geopolitical forces, economic wealth of the nation, military threat projections, etc.) to the microscopic (e.g., availability of steel and skilled labor, etc.). For purposes of investigating the impact of variation on submarines, the overall system complexity must be reduced in scope. One such sub-system pertains to the submarine hull[1]. On the manufacturing front, variation is of particular significance since raw sheet steel much be transformed into a complete hull form subject to geometric design tolerances and a 30 year lifetime of hydrodynamic forces in the corrosive sea water environment.

Within this transformation—turning flat steel into a submarine hull—there are numerous processes that have the potential to impact the variation of the product. This research effort will focus on the variation which may result from such areas as: geometric design parameters, joining methods, alignment techniques and datum control, material properties, measurement methods, cutting and forming practices, and others. Each of these areas consists of many different processes and actions, some automated, others manual, that contribute ever-greater levels of complexity and variation to the end product. The intent of this research is to better understand the systematic identification of the Key Characteristics (KC) which influence variation. KCs are just one of the techniques of VRM that are currently under investigation by Professor Anna C. Thornton and her research group within the Center for Innovation in Product Development (CIPD) at the Massachusetts Institute of Technology (MIT).

[1] The "hull" is the exterior structure of the submarine which is capable of protecting the crewmembers and internal equipment from the sea environment at all operating depths.

A more detailed discussion of KCs, as well as other VRM practices, is contained in Chapter 2 of this work.

The current method of submarine production uses lessons and knowledge from past experience to arrive at an acceptable finished hull section, ring stiffened cylinder, shell, or circular frame subsection (each of which is described in detail in Chapter 3). This practice requires significant resources (labor, time, and material) and may not be an optimal methodology for overall cost reduction. Only after a more thorough analysis of the existing efforts are understood can comparisons be made with the "best practices" of VRM methods utilized in other industries outside of the military or government programs. The hypothesis being that a better understanding of the existing process—via a systematic critical understanding of current practices and the identification of those Key Characteristics (KC) proven to be essential to high quality—will enable potential design and or process improvements which may lead to a favorable return on investment (ROI).

1.4 Research Sponsors

The submarine specific research was made available through the cooperation of the Electric Boat Corporation and the Quonset Point Facility. The supporting academic research and literature stems from the ongoing work of the CIPD at MIT and with the Center's ongoing sponsors. These organizations cut across industries and cover both public and private sectors to provide a diverse and insightful body of knowledge in current product development initiatives.

The funding, in the form of MIT tuition, was provided by the U.S. Navy as part of a graduate level training program for active duty naval officers in the field of Naval Construction and Ocean Engineering. This research project is, however, an independent work by the author and does not in any way reflect the opinions,

assertions, or policies of the U.S. Navy or Department of Defense. All information contained herein is unclassified and free of government or industry proprietary data.

1.5 Thesis Outline and Contribution

This thesis will perform a detailed VRM review of the submarine hull manufacturing practices employed by QP. By conducting a detailed review of a specific and related series of manufacturing processes, it is believed that the methodology presented can then be extended in scope and applied to other areas of manufacturing within the submarine fabrication process. This will be highlighted by comparing the submarine hull manufacturing processes with commercial aircraft manufacturing processes. Such a comparison will add fidelity and merit to the KC methodology and allow continued self-review and assessment within QP well into the future. The author is profoundly hopeful that such reviews will strengthen the whole of the submarine and ship manufacturing industrial base infrastructure within the U.S. Navy and all of the Department of Defense manufacturing programs.

In addition to the introductory and background information presented thus far in Chapter 1, the following summary provides an outline of the ensuing work. Chapter 2 presents a literature review and description of Key Characteristics. In addition, a brief overview of other successful VRM practices is presented. The specific application of the KC methods are contained in Chapter 3 along with a summary of the data collected for the Quonset Point processes. In Chapter 4, the practices of The Boeing Company (Boeing) are presented as a supporting case study. Boeing's VRM practices[2] are particularly useful since the aircraft fuselage manufacturing processes

[2] The Boeing Company refers to their VRM program under a separate name—Hardware Variability Control (HVC)—but the general principles are consistent with the aggregate VRM summary presented herein.

are believed to be in part similar to the submarine hull fabrication techniques reviewed at QP. Finally, Chapter 5 provides with conclusions and recommendations for future effort in the field.

2.0 Variation Risk Management Practices and Research

2.1 VRM Discussion and Definition

Recall the following question posed in the introductory portion of this effort: What is *variation*? *Variation* is the deviation from the design nominal value or specification that develops during a given manufacturing process, either in a single or multiple series of fabrication steps. It is a result of the confluence of interactions between design intent, material properties, fabrication processes and fixtures, assembly tolerances, labor content, and the inherent uncertainties present in any system.

All manufacturing organizations are exposed to variation and some are more sensitive to the impact that variation may have on the performance and acceptance quality of the final product. Variation Risk Management (VRM) is the broad category of techniques that attempts to continually identify, assess, and mitigate the risk that variation will have on the final cost and performance of a product [Thornton 1999a]. Management of this variation risk is vitally important to companies since out of control variation can lead to increased scrap rate, additional rework, poor quality, and diminished customer satisfaction. To counter these adverse reactions to variation, VRM practices attempt to quantify the potential pitfalls early in the product development process. The early identification allows a more aggressive effort to contain the costs of variation in both recurring and non-recurring events [Clausing 1994]. Early identification and containment of variation is not a casual event. It requires persistent and overt action within the product development process. This is an essential characteristic of any successful VRM process.

Successful VRM polices require considerable understanding of the underlying processes, communication among and across designers and manufacturing engineers, and a committed sustained level of managerial support [Ertan 1998]. The success of any VRM program can be traced back to the three fundamental phases of VRM: *identification*, *assessment*, and *mitigation*.

2.1.1 Risk Identification

The initial step in a VRM practice is to determine where the variation is—what is it and where along the product development and manufacturing process it originates or is amplified to a critical level. To conduct this phase, an engineer or designer investigates the various system design attributes and evaluates whether variation in an important parameter can substantially degrade the product's performance or quality. Inclusive in this investigation is the subsequent impact that variation in one parameter may have in potentially magnifying the variation associated with another parameter or group of parameters as manufacturing progresses. This identification process consists of two steps: identifying the risk area itself; and understanding the contribution of the risk to the system [Thornton 1999a]. The later is referred to as a risk "flowdown" (Figure 1) where the various levels of the system are broken into a more fundamental step-wise view and evaluated individually in the subsequent risk assessment phase of VRM.

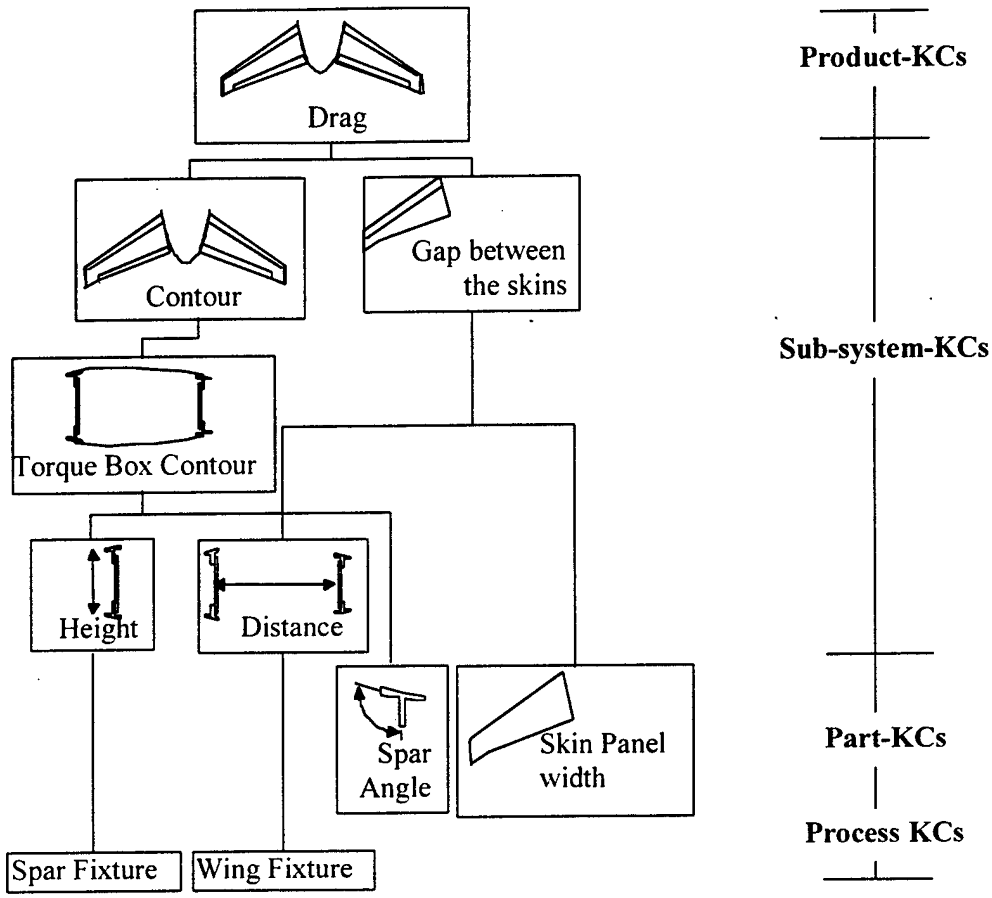

Figure 1: KC Flowdown Diagram [Thornton 1999b]

In this illustration, a better understanding of variation is developed by tracing the inter-process relationship of variation contribution for an aircraft wing KC. The aircraft wing drag has been identified as a critical product design parameter. The manufacturing process elements that could impart variation are flowed down through exploration of the linkages among the various production phases. By developing this hierarchy of linkages between these discrete events—processes and components—the VRM process identifies the potential critical few design features or manufacturing steps that impact the final product performance, which in this case is drag. In many cases, sub-system elements may be present in other products and their impact evaluated across system boundaries for an even greater effect. In other words, controlling the source of variation at a single process or sub-system level can have far

reaching benefits because multiple downstream processes are improved by correcting a single point in the production chain. A more detailed discussion of the flowdown methodology is provided in section 2.3 and applied to the QP process.

This two step risk identification process—identifying a variation risk area; and understanding its subsequent contribution to the overall system—is far from obvious, however. In practice, it is beyond the capability of many engineers and designers because of their individual focus and role within the entire system. Most designers are highly specialized in their particular area of expertise, but often unaware of their design decision impact to the whole of the product development process. They may correct one source of variation noticed at their level, but in so doing create more variation risks later in the process. Trying to make every designer an expert in all phases of product development and manufacturing is sometimes suggested as a solution. Accounting for every aspect of variation risk in this manner is simply not plausible. Such an effort would quickly overwhelm the company that tries to identify every and all possible causes of variation. There is considerable literature that demonstrates that successful firms focus on those essential few areas that promise the most benefit when brought under control early in the product development process [Whitney 1988; Taguchi and Clausing 1990; Fowlkes and Creveling 1995].

The process of identifying only those critical few parameters which impact product performance and focussing effort in reducing the variation risk is commonly referred to as Key Characteristics (KC) [Thornton 1999a]. KCs, the major methodology explored in this research, is just one of the many VRM practices presented in section 2.3.

2.1.2 Risk Assessment

The next step in VRM is to assess the risk associated with the parameters identified in the previous step. There are several methods available to assist in the risk assessment

portion of VRM, but the most common is Taguchi's Quality Loss Function[3] [Taguchi 1993]. Figure 2 illustrates the loss function as presented by Taguchi.

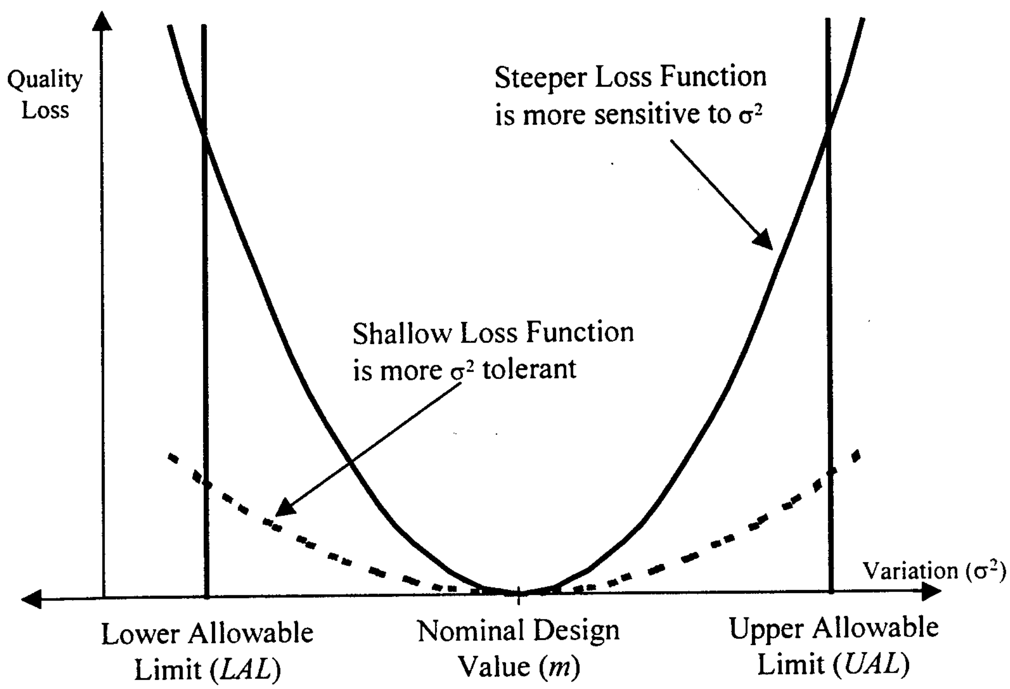

Figure 2: Taguchi Quality Loss Function

As depicted in Figure 2, the system variation is assumed to vary uniformly on either side of the nominal design value (*m*). For example, a part can be larger or smaller than design; or a gap can be greater or less than nominal; etc. Taguchi represents the variation of the nominal design value (σ^2) as a quadratic function. As variation increases to either side of the design value, more and more quality loss is injected into the system. Since this loss of quality increases about the design value, the steeper loss functions introduce more quality loss and increased cost for a given value of variation. Hence, the steeper the loss function, the more important it is to identify a

[3] Taguchi's Quality Loss Function is often referred to as the Cost Loss Function. The former will be used in this effort.

feature as a critical parameter. The mathematical expression for the quality loss due to variation from nominal for a given system parameter (*i*) for characteristic (*y*) is denoted as $L_i(y)$. By convention, if y = m, the design nominal value, then there is no loss such that $L_i(m)=0$. As the characteristic varies about *m* within an acceptable design tolerance band from y = m – LAL to y = m + UAL, then Taguchi's loss function is:

$$L_i(y) = k_i (y - m)^2 \qquad \text{(Eq. 1)}$$

where k_i is a constant relating the cost of a defective product (C_i) and the magnitude of the deviation of the characteristics from nominal [Taguchi 1993]

$$k_i = \frac{C_i}{\left(\frac{UAL_i - LAL_i}{2}\right)^2} \qquad \text{(Eq. 2)}$$

The quantified cost impact due to a defective product must be specified to fully exploit this technique. Such cost can be in terms of additional labor or fixturing during rework, reduced functional life due to wear, etc. Unfortunately, this cost function is rarely known for the vast majority of processes. For more complicated systems with many parameters, the quality loss must be known for each parameter, further complicating the analysis. The implication of this reality is that it is necessary to determine system level quality loss across a larger system of systems. Consider, for example, the aircraft wing example illustrated in Figure 1. In this case, the quality loss for variation in wing drag [L_{drag}] would need to be determined. In addition, the quality loss due to the wing weight [L_{weight}], interface to the fuselage [$L_{interface}$], etc. [L_i], would all represent systems of variation contributing to the larger system of systems—the final assembled aircraft. Notwithstanding, the method is simple to

apply if the quality loss function can be determined, but it is often a conservative assessment of risk. It also assumes that the quality loss for negative variation (defined as a point to the left of nominal in Figure 2) is the same as that of a positive variation. In some manufacturing situations this is not the case, however. Recent work by Thornton [Thornton 1998] develops an alternate risk assessment measure which allows for an asymmetrical quality loss function. This research asserts that there are instances when variation gradually incurs a quality loss if the deviation is to one side of nominal (C_u) but results in a sudden and substantial step degradation when the variation is to the other side (C_l). Thornton provides an illustrative situation for a welded component joint, shown in Figure 3.

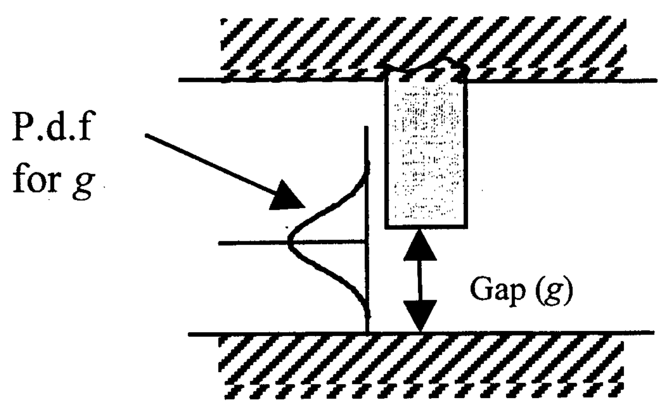

Figure 3: Illustration of a Weld Root Gap

The larger root gap results in additional filler material and time for welding and adversely impacts the quality loss as size increases. The converse relationship is limited, however, in that a small root gap may initially show the same behavior, and thus be adequately represented by Taguchi's method, but there may be a point where the root gap is closed and requires a part to be trimmed before assembly. This trimming operation injects a step increase in the quality loss function and hence skews the impact of variation to favor the larger gap over the impact condition, Figure 4.

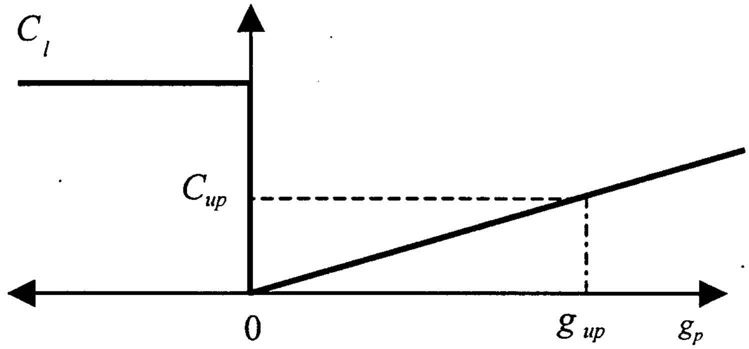

Figure 4: Asymmetrical Cost Loss Function

Notice in Figure 3, that the gap itself (g) is represented by a probability density distribution, assumed normal for this example, but readily adapted for a particular firm's experience. Thornton's work is very insightful because it applies a separate cost loss function and tolerance function. These separate functions can more accurately represent the actual processes present in many manufacturing scenarios, beyond the weld gap illustrated here, when there is a clear asymmetry in the impact of variation on the resulting product's performance [Thornton 1998].

In either method above, the same detailed system and process steps are requisite for the method to provide reasonable outcomes. The critical design parameters must be understood to enough fidelity that the variation in each parameter and process, as well as the resulting quality loss function(s), should ideally be quantifiable. This is again not a trivial undertaking and there are many practices used in industry to address this difficulty. Many of these will be addressed in section 2.2 and a detailed description provided for the Key Characteristics Flowdown method follows in section 2.3.

A completely different method of risk assessment takes the approach of developing then managing a "variation budget". In this assessment technique, a VRM program typically uses two process capability measures:

1) the ratio of a product's tolerance to variation divided by the variation spread of a particular process (R, where $R=6\sigma$ is commonly used as determined from product design specifications); and

2) the ratio of the difference from the design mean (*m*) to the nearest limit of product tolerance (*UAL* or *LAL*) divided by 50% of the total variation spread for the process (6σ) [Liggett 1993].

$$C_p = \frac{UAL - LAL}{R} \qquad C_{pk} = \min\left(\frac{UAL - m}{R/2}, \frac{m - LAL}{R/2}\right)$$

(Eqs. 3 and 4)

The first ratio, referred to as C_p (spoken "C sub P") must be greater than or equal to 1.0 for a process to be capable of delivering the required part tolerances. For the common Six Sigma[4] processes (i.e., $R = 6\sigma$) a $C_p>=2.0$ is used, which represents a process spread covering 75% of the specified limits to product tolerance. The second measure of process capability, the available tolerance, is referred to as C_{pk} (spoken "C P K"). As with C_p, C_{pk} must be greater than or equal to 1.0, and is typically greater than 1.5 for a Six Sigma methodology. These ratios are a portion of the more broad practice of Statistical Process Control (SPC) and are more clearly understood in graphical form, Figure 5.

[4] Six Sigma is the method developed by Motorola and has been widely adopted in many manufacturing organizations.

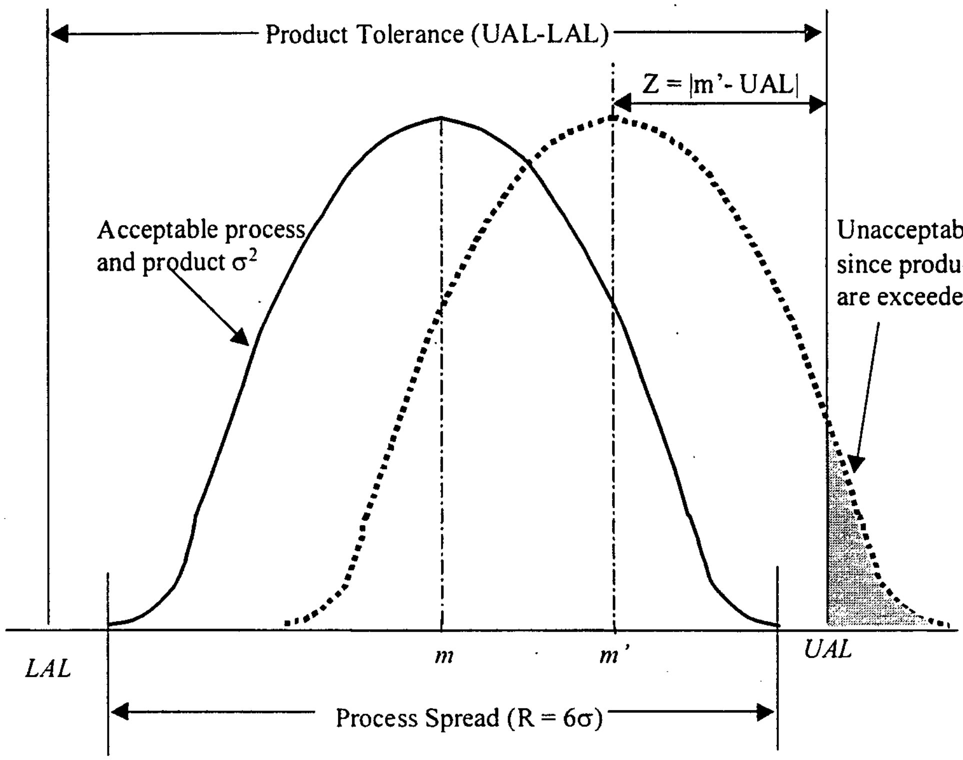

Figure 5: Process Capability Assessment [adapted from Liggett 1993]

In this figure, the C_p greater than 1.0 is represented by the solid curve where an allowable product variation (*UAL-LAL*) is larger than the capability of a particular process ($R=6\sigma$). This allows for some drift of a process—as a consequence of human interaction, fixture differences, tool wear, etc.—about the process design mean (*m*) without resulting in unacceptable product variation (denoted as the shaded region of the figure). A less desirable process with a mean of *m'* is shown in Figure 5 as the dashed curve with shaded region beyond *UAL*. C_{pk}, can be better understood from Figure 5 by recognizing that as the available tolerance ($|m'-UAL|$ or $|m'-LAL|$) decreases—shown as the vector Z in the figure—the amount of unacceptable variation outside the specified product limits increases (i.e., the shaded region). The degree of rejection is directly related to the area of the shaded portion of Figure 5, which shows the out of tolerance products generated from a given process.

In this VRM assessment technique, SPC is maintained on contributing processes over time and on the various product "pieces" or sub-systems. The SPC information covers only those processes that are identified as contributors to the variation being investigated. SPC data will then identify areas of variation in parts and processes. As a part progresses through the manufacturing process, variation is added. Therefore, the total allowed tolerance for the final product is gradually consumed by the manufacturing steps. To make sure that the continual variation risk does not result in an unsatisfactory end product, effort to control variation is done by matching product with process. As long as the designers understand the interaction of process and product, they can budget their allowed variation down to the individual feature level. In reference to Figure 5, the goal here is to maximize the magnitude of vector Z, where $Z = \Sigma (z_i)$. This minimizes the shaded area of unacceptable product variation. Here, Z is a system level variation and each manufacturing step adds some variation z_i at the sub-system or process level. The limitations of this technique stem from the volume of SPC data required, even for simple products of one or two parts and processes. The data collection and analysis burden and costs explode exponentially for more complicated systems of hundreds of operations on thousands of features. SPC on complicated systems is further burdened by the need to maintain consistent tooling settings, operator actions on a recurring basis, etc.

As detailed above, both of industries' most common risk assessment techniques still leaves unanswered the question of which design critical parameters to evaluate, either by Taguchi's method or SPC using C_p and C_{pk}. Such an evaluation is often qualitative in nature and highlights only the causal relationship between process and product. The quality of the assessment depends on the level of understanding of the existing manufacturing and design infrastructure. A quantitative analysis is more desirable, for obvious reasons, but is also extremely difficult to generate [Lee and Thornton 1996a]. The existence of a complete data set relating product features and variation through the process capabilities via a known cost loss function is infrequent

even in the best VRM program. As in the discussion of risk identification, one available technique that aids in the systematic process of identifying and assessing variation is the Key Characteristics methodology which soon follows. However, the final phase of VRM—mitigation, should be discussed before covering the KC method in detail in section 2.3.

2.1.3 Risk Mitigation

In the introduction a very simple question was presented concerning variation: Can the *variation* be substantially reduced? Ideally this is the ultimate form of mitigation but, as the assessment theory suggests, it is not realistic. Since mitigation is really the first VRM phase where a cost-benefit analysis surfaces, most of the effort in VRM techniques is in this phase. Risk mitigation utilizes both qualitative and quantitative analysis of a firm's process and product to determine if changes are required in either or both process or design [Ertan 1998]. For the reasons discussed in the previous section on risk assessment, the availability of quantitative information is most often lacking. To compensate for the lack of quantitative information in VRM, many companies are pursuing two paths. First, there is an ongoing effort to develop better VRM tools and practices that generate reliable quantitative variation data for system and sub-system processes and products. Several of these are presented in this chapter. A second approach involves improving the quality of the data. Many firms have found that cross-functional teams consisting of designers, manufacturers, and suppliers can greatly improve the VRM risk mitigation phase [Wheelwright and Clark 1995]. The degree of managerial support and sustained commitment to these teams has also been demonstrated as a vital component in a successful mitigation strategy [Ertan 1998].

Notwithstanding the importance of an effective risk mitigation program, one is lead to ponder—How it can be done? There are two aspects of variation risk mitigation. The

first involves change in the form of design improvements. The second requires change in the form of process improvements [Thornton, *et al.* 1999c]. *Change* is the common theme, but changing an existing process, design paradigm, product specification, etc., comes with substantial cost, burden, and risk [Storch, *et al.* 1995]. Utterback discusses the almost insurmountable challenges that organizations must manage when confronted with the need to change [Utterback 1996]. More often than not, established organizations become "set in their ways" and fail to act upon obvious signals for change. These signals originate from the external marketplace or internal to the organization from personnel familiar with current and projected trends. The context for recognizing and enacting change is usually in response to new products or technologies entering the market. The author asserts, that the same is true internally when companies fail to evoke the necessary variation mitigation programs because they are comfortable within the limitations of their present system. They may be willing to make minor incremental changes to the system, but they are hesitant to make the large changes that are sometimes necessary. Since the true return on investment (ROI) for a VRM process is usually determined far removed and much delayed from the individual actors involved in implementing the program, there is an added complexity of aligned incentives working against developing successful VRM programs. Again the importance of high level, committed, and sustained managerial support is essential.

Some have suggested short sighted approaches that point to variation and claim the optimal risk mitigation strategy is one which inspects the variation out of the product—through scrap or rework—thereby eliminating the "problem" [Jay 1998]. This method of risk mitigation may be a cost-effective solution for simple high volume items (e.g., paperclips), after all bad clips can be recycled or discarded at negligible unit cost. However, such an approach is ominous when one considers more complicated systems with high value added processes and material—monolithic poor cementatious structure, ships, aircraft, etc. Clearly if variation is exceeded

during the final stages of manufacturing, the product cannot be scrapped. Even in the less extreme case, such products are often extremely cost prohibitive to rework. An intermediate example from the electronics industry provides a more palpable illustration. Correcting a flaw in the earliest stages of design is 10^4 times less costly than finding and correcting the flaw in the manufacturing stage—*4 orders of magnitude difference* [Himmelfarb 1992].

In these situations, a more methodical risk mitigation scheme is warranted . If such a scheme can be developed for the extreme case, then perhaps it can also be applied to the paperclip example to further reduce scrap in a cost-effective manner. This is the logic driving the wide array of industry practices being pursued in the risk mitigation field.

2.2 Survey of the Current State of Industry Practices

There are dozens of well-known VRM practices currently used across a spectrum of industries. This section provides a cursory summary of many of the more common techniques. It is not the author's intent to cover the details of each, rather to provide the reader with a survey of VRM techniques which may serve as a useful reference. The most extensive body of work in VRM is ongoing at the Center for Innovation in Product Development at the Massachusetts Institute of Technology under the direction of Professor Anna C. Thornton. The majority of the information in this section is a direct result of former and current research projects under her tutelage. Specifically useful are the current efforts expanding work by Ardayfio and Ertan [Ardayfio 1998; Ertan 1998] in populating MIT's "KC Maturity Model" with twenty-two industry practices. These practices are summarized in Table 1 according to the fundamental VRM phase it best corresponds—identification, assessment, and mitigation. In addition to these three VRM phases, the maturity model also addresses the category of supporting information, which is also included in the table.

Table 1: Maturity Model Summary[5]

Identification	Assessment	Mitigation	Supporting
1. VRM Initiation	4. Risk Prioritization	12. Quality and Process Improvement Objectives	18. Documentation
2. Risk Definition	5. Risk Validation	13. Robust Design Tradeoffs	19. Training
3. Customer Interaction	6. KC Flowdown	14. New Technology Introduction	20. Integrated Product Teams
	7. Variation Modeling	15. Cost-Benefit Tradeoffs	21. Management Support
	8. Supplier Interaction	16. Reuse/Legacy Data	22. Incentive Structure
	9. Measurement Plans	17. Prioritization	
	10. Capability Feedback—Product and Process		
	11. Tolerancing & Dimensioning		

The maturity model attempts to evaluate the effectiveness of these practices across a survey of industries. For example, the KC Flowdown practice has multiple forms. Both the direction of "flow" bottom-up or top-down; and the methods to identify the

[5] The KC Maturity Model is dominated by methods developed from the Key Characteristics methodology. The more generic VRM practices are also valid and are presented here based upon current research [Thornton 1999c].

critical risk areas—Quality Function Deployment (QFD), Variation Analysis, which propagates further to the tools used in the technique, such as Variation Simulation Analysis (VSA) software. Since the focus of this thesis is on the Key Characteristics method, which is just one specific portion of VRM, this technique merits a more detailed discussion.

2.3 Key Characteristics

Implementing a VRM program, though potentially showing substantial cost avoidance and improved quality on projects, is no small undertaking. A successful VRM program requires training, communication, commitment, technical understanding, data collection, and numerous other characteristics [Ertan 1998]. Since the process involved in actually identifying, assessing, and the formulating a mitigation strategy is both complex and costly, only those essential parameters that determine a product's sensitivity to variation must be considered. This portion of the VRM discipline is called the Key Characteristics Methodology.

> *"Key Characteristics are the product features, manufacturing process parameters, and assembly features that significantly effect a product's performance, function, and form"* [Lee and Thornton 1996a].

As the manufacturing industry's interest in VRM escalated through the 1980's and continued through the 1990's, so too has the popularity of Key Characteristics developed. The KC method is founded on the strong evidence that variation present in some critical design parameters can significantly and negatively impact the overall cost, performance, and quality of products [Lee and Thornton 1996a]. The previous portions of this report have attempted to amplify this impact relationship. It is now time to delve into the particular details of KCs.

2.3.1 Definitions

The KC component of the VRM practice is sometimes referred to under the titles of Critical Parameters (CP), Critical-to-Function (CTF), and Dimensional Risk Management (DRM), and Hardware Variability Control (HVC), to name a few. Alternate nomenclature aside, the KC approach is a technique that attempts to focus the VRM effort on only the most "important" product and process features. Developing tools and techniques to identify, isolate, and prioritize KCs has been the focus of much of the early research in the area. This work was necessary to overcome the recognized and problematic lack of such methods. As early as 1996, the state of KC practices in industry included such obscure techniques for evaluating KCs as basing action on a "feel" for how product features would effect ultimate customer requirements. This qualitative nature of KCs and VRM in general has resulted in long lists of KCs with corresponding management plans that may or may not have been founded upon a sound understanding of the manufacturing capability or costs of variation for a particular KC [Lee, *et al.* 1995; Lee and Thornton 1996b]. Thus a more systematic method was needed and the following KC definitions developed:

KCs fall into two categories: product characteristics and process characteristics[6].

> Product Key Characteristics are those product features that, if subject to variation about the design nominal value, result in significant adverse impact on the resulting product's quality—performance, function, form.

[6] Lee and Thornton's, *et al.* earlier work further classified process KCs into two type—manufacturing and assembly. In addition a forth classification of "StatKC" was defined as high risk KC. Current research generally considers the two broad categories presented here—product and process KCs.

Process Key Characteristics are the assembly and manufacturing parameters that, through such mechanisms as machine tooling and/or fixturing, contribute to product variation.

Note that these definitions are not independent. For example, a highly methodical process may inject only minor amounts of variation into the product, but if the product design is intolerant to even modest variation, then the resulting system may fail to deliver a satisfactory product to the customer. The converse is also true. When a product design is methodical, the designers still rely upon some form of process control such that even tolerant designs cannot be reasonably expected to successfully proceed through a random manufacturing process where round pegs are hammered through square holes. Even great designs can fail if critical process variations are not understood in the manufacturing process.

The product KCs are the sole result of design requirements and specifications. The process KCs are based upon the current manufacturing system of man and machine. Recognizing the linkage between the two KC types is at the heart of a successful VRM program using this technique. This is accomplished by employing a KC Flowdown analysis.

2.3.2 Flowdown

A flowdown traces a product's design features and manufacturing processes through a series of causal relationships to gain an understanding of the impact of variation on the final product. This process was presented briefly in Figure 1, section 2.1.1, but is repeated here for easy reference and discussion (Figure 6).

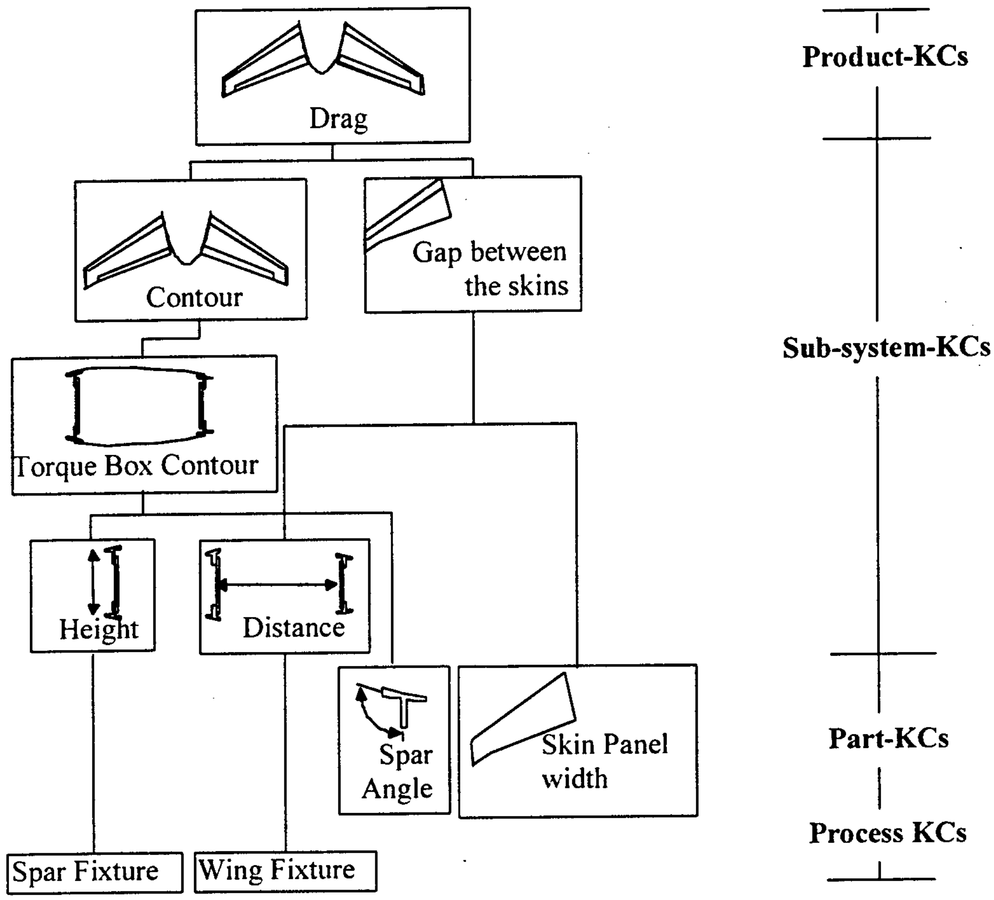

Figure 6: KC Flowdown Diagram [Thornton 1999b]

Figure 6, illustrates a KC flowdown for aircraft wing drag. This example is simplified to highlight all of the essential features of the method but can also be applied with much greater detail in actual implementation. The top of the figure represents the "final product" from the perspective of the flowdown analysis. In this application wing drag has been *identified* as a key feature, so the flowdown begins at this product KC. Listing the wing drag KC begins the first phase of the VRM process, an essential parameter impacted by variation has been identified. The manner in which the KC is identified can arise from customer specification, engineering performance criteria, etc. In complicated systems, the process of identifying a narrow but essential number of variation sensitive KCs is accomplished

through experience and knowledge of the product. Companies are finding that cross-functional teams (CFT)[7] are very much effective in accomplishing this task.

From the final product KC the flowdown process involves *identifying* the sub-assemblies or components that contribute to the final product. In Figure 6, these sub-system KCs are wing contour and gap. Each of these is further dependent upon prior stages of manufacturing. Notice that the torque box depth (referred to as "distance" in Figure 6) influences both contour and gap such that any alteration to depth variation must be evaluated against the impact on multiple features. Tracing the sub-system product KCs down further, one arrives at the process KCs. Note that process KCs can also occur in other portions of the flowdown, but generally result near the bottom of a top-down flowdown. The reasons for this arrangement are twofold. First, by their definition, product KCs are independent of the manufacturing and assembly processes necessary to fabricate the product, so the sub-system product KCs are usually based on the engineering specifications of the design. Secondly, the process KCs represent the "end of the road" where an engineering design becomes dependent upon a manufacturing process. This foundation on process serves as a reality check during the course of developing and subsequently evaluating a KC flowdown. If a design is incapable of ultimately satisfying the product KC because existing processes result in unacceptable variation, then the designers and manufacturers need to reevaluate either the design, the process, or both. If this is done before actually going into the manufacturing stages, a great deal of money can be saved. There is evidence of this assertion in the Ford Windstar vehicle program where existing processes were identified early as incapable of meeting the variation controls needed in the end product. Adjustments made before production are estimated to have saved between $5 million and $10 million in rework [Sweeder 1995].

[7] The term cross-functional team (CFT) will be used interchangeably with integrated product team (IPT), integrated product development teams (IPDT), etc. to represent a team of professionals from varied fields of expertise assembled to address a focused design or manufacturing effort.

Now that a single final product KC has been flowed down through multiple sub-systems and processes, the extension to multiple "final" products should be clear. In the wing drag example, there may also be a KC for the wing's join to the fuselage that interacts with many of the sub-systems and processes already highlighted, these same processes many again link to a vertical stabilizer alignment KC, and so on. The KC flowdown method can thus be applied across multiple top-level product KCs to provide a complete systems view of the most critical variation sensitive features. In this illustration, the KC flowdown started at the product level and flowed down to the process level. This type flowdown is known as a *top-down* analysis. It differs in emphasis from another common flowdown method—the *bottom-up* approach.

Top-down KC flowdown[8]—is most common for new product design initiatives or significant re-designs. In these situations, the critical product characteristics can be identified in advance and the design and manufacturing process investigated for their ability to satisfy the final product KC. The subassembly product features are analyzed, along with the various manufacturing processes to ensure that the confluence of their individual process and subassembly variations does not exceed the allowable design tolerance. To perform a top-down KC flowdown, the product is decomposed into many components for each product KC. As more product keys are identified, the analysis gains complexity, particularly, as in the torque box depth example above, when the subassembly processes impact multiple product KCs.

Since the top-down method begins at the final product features, industry is increasingly relying on the final customer to identify the important features—KC *identification*. Product designers are finding the early end-consumer involvement allows better analysis during the flowdown to manufacturing. They begin to

[8] The nomenclature of a "top-down" or "bottom-up" method of a KC "flowdown" is somewhat confusing, but is consistent with the research that has taken place in KC methods.

understand the limitations of their existing manufacturing processes, in coordination with the manufacturing engineers with the design team, which allows potential variation impacts to be avoided before the design begins full scale production. The method of flowing down the impacts of previous manufacturing steps begins the *assessment* portion of the KC method. The variation risk is assessed based upon the aforementioned interactions. The design and manufacturing engineers being a process determining the quality loss or impact of failure to meet a design tolerance. If a particular production sequence results in an unacceptable variation condition, then action is taken to change the design, the process, or both, to alleviate the conflict. Similar efforts are repeated as necessary to verify only those significant parameters that are actually "key characteristics" and need to be controlled. This action of assessing variation risk in a KC and changing the process is the final segment of the KC method—*mitigation*. In many instances, however, a design and manufacturing process may already exist. A top-down method is therefore not practical since changing the entire process to correct a variation problem is prohibitively costly. In these situations, the bottom-up KC method is employed.

<u>Bottom-up KC flowdown</u>—is similar to the traditional troubleshooting approach used in correcting a targeted production or design "flaw" which generated unacceptable variation. In these instances, the *identification* portion of the KC method begins not with the final product, but with the suspect process and/or design parameter. The KC *assessment* then traces the variation induced at a lower level throughout the remaining production sequence to determine the impact on final product performance. The bottom-up method is useful when the ability to start with a clean sheet of paper is unrealistic. In a manufacturing setting, for example, the capital investment in tooling may mandate a different variation control technique than would optimally be enacted in the top-down method. The bottom-up approach is better suited to more qualitative analysis when the ability to quantitatively determine the variation quality loss function is lacking. Since the later is very common in industry, the bottom-up KC

flowdown is more commonly encountered. It is far easier to identify and assess a failure once it occurs and is noticed. Data on recurring rework, excess labor content, high scrap rate, etc. serve as red flags that there is a variation problem. Attacking these issues through a search for and elimination of the root cause is the *mitigation* portion of the KC method and is the goal of the bottom-up approach. Unfortunately, by the time sufficient data is collected, whether statistically significant or not, the cost of the excess variation will have already caused a negative impact on a firm's performance. The post mortem aspect of the bottom-up technique is a severe limitation. To further understand the entire KC method the next section of this research presents a typical KC process and introduces a new method derived from the top-down and bottom-up techniques here.

2.3.3 KC Method

Thornton describes a typical KC process as a two distinct parts. Firstly, KCs are identified and assessed in the flowdown technique. Secondly, the KC assessment and analysis leads to a variation risk management scheme to mitigate the impact of variation [Thornton 1999b]. This process is presented in Figure 7 to show the sequence of events. The first phase of the KC process, is ideally conducted during product design. As shown in Figure 7, during this portion of the KC method, the KCs are identified and their impact assessed. These actions are generally accomplished by the implementation of the flowdown methodology. In practice, these steps may generate extensive lists of possible KCs that appear essential in controlling variation. In some cases, when the product in question is already in production, the total number of identified KCs exceeds the number which are controllable without substantial capital investment and time delays. In these situations, the top-down KC flowdown produces more KCs in subassembly production processes than can be effectively employed while, at the same time, the bottom-up approach may not capture all of the necessary KCs—particularly for more complicated products. Thus, an alternative flowdown practice is desirable.

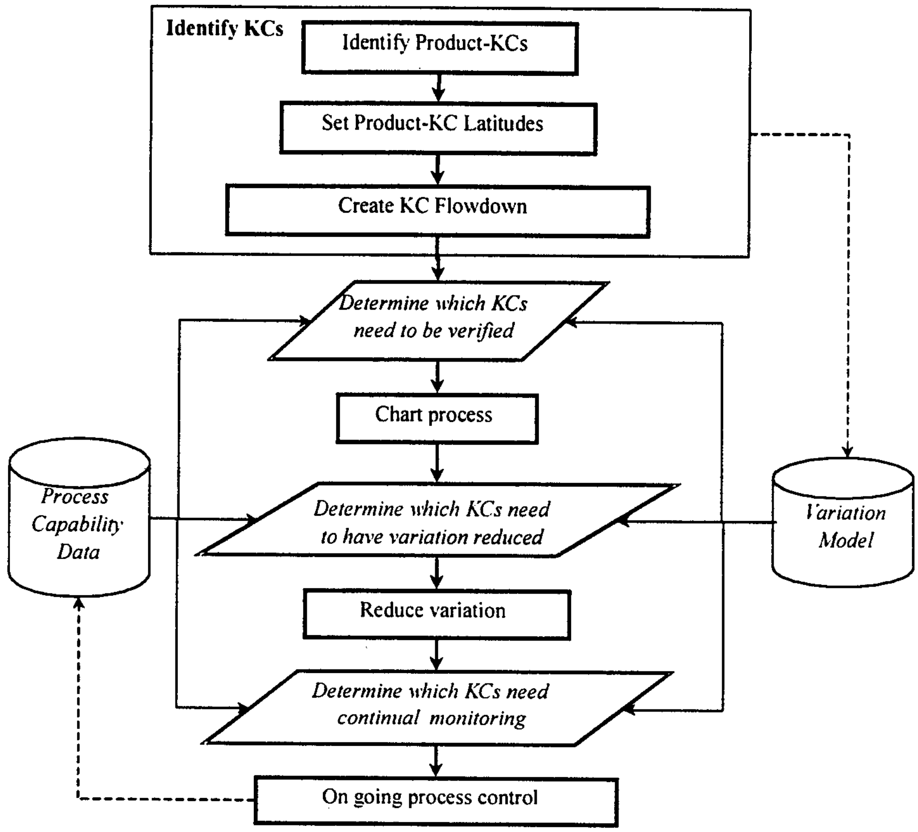

Figure 7: Typical KC Process [Thornton 1999b]

The author builds upon the merits of both top-down and bottom-up approaches and suggests an alternate KC flowdown method named *process-to-and-from-design (PTFD)*. This concept involves simultaneously investigating the impact of variation *from* the processes *to*wards the finished product, as well as the demands relegated *to* the production processes *from* the design specifications. Both process characteristics and product characteristics are represented by this method. The difference from the top-down or bottom-up approaches lies in the fact that the to-and-from-design logic drives a KC "solution" by finding the common KCs highlighted in both directions. The previously identified methods developed a KC solution in one direction or the other and may either omit some otherwise significant KCs; or include other less significant parameters by identifying too many KCs. There are, however, similarities

with the other methods. In this technique, the "*process-to-design*" resembles the bottom-up approach where the feature level KCs flow into downstream production steps towards the final product design. Unlike the bottom-up method, however, this technique stops short of tracing every KC linkage and performing an exhaustive KC identification, assessment, and mitigation program. Instead, the PTFD method first attempts to "pick the low hanging fruit" for the more easily identified KCs. Following the first cut, the process-to-design PTFD approach then refines the investigation and identifies less obvious parameters. This PTFD path identifies the known processes and practices and attempts to provide a means to control variation by building from the existing production infrastructure. This approach lacks the desired preliminary analysis that the top-down KC flowdown presents. By tracing the same system in the other direction—*process-from-design*, however, the proposed PTFD methodology does provide many of the benefits of the top-down approach.

In the "*process-from-design*" direction, the variation demands generated by the design function are analyzed for their impact upstream in the manufacturing sequence towards the process feature level. As in the previous concept, this PTFD logic does not attempt to cover the same complete set of critical KCs as the top-down technique would suggest. In the proposed PTFD KC flowdown, the designers are most knowledgeable about variation on one end of the system, while the manufacturing engineers more fully understand their area of specialization at the other end of the system. As they both work towards the middle of the process-design interface, they help highlight those KC elements that appear in both directions. In other words, the PTFD techniques draw focus to those KCs—in either product design or process capability—that can simultaneously: 1) mitigate the variation causing an ongoing concern (as does the bottom-up method); as well as 2) act as a strategic risk mitigation measure by identifying necessary design changes which match existing processes (as would be the case in the top-down KC flowdown).

Referring back to Figure 7, the second part of the KC process attempts to focus the designers and manufacturing engineers onto only essential KCs. The argument just presented supports this desire by reducing the number of dead ends pursued in top-down or bottom-up flowdown. The PTFD method generates convergence in both of the previous techniques. This convergence thereby allows the more effective use of the KC process in general. More emphasis is placed on process capability enhancements, variation risk management techniques, process control, etc.

Having defined a new KC method and the PTFD program, the ensuing case analysis shows the merits of the methodology structure for modular submarine hull construction. Though the case example is specific, the technique can be applied in other situations. This later situation represents the longer-term benefit of this research effort.

3.0 Case Study: KC Method Applied to Modular Submarine Hull Construction

3.1 Introduction and Outline

The major motivation for this research project was to better understand the current submarine hull fabrication practices at Electric Boat Corporation's Quonset Point Rhode Island facility (QP). The original concept for the research topic was presented to the author by a member of QP who expressed a desire to sponsor a research project with MIT's CIPD and the KC efforts. This idea met with the interests of the author in submarine design and manufacturing and opened a spectacular opportunity to collect data in an actual setting as an alternative to a purely academic endeavor.

The goal of the project is to formulate a systematic method for evaluating the hull manufacturing processes which may then be applied, in principle, to other aspects of QP's manufacturing efforts. To accomplish this task, the following method was pursued. Firstly, an understanding of the QP facilities and practices was investigated through site visits and interviews with QP personnel.

The actual data collection method is also discussed in that it plays a critical role in the research. Not only does the data provide a means for analysis, it also highlighted some limitations. The low production rate of submarines affords limited data volume. As the data is limited, so too is the statistical significance of the results. This must be recognized, but does not diminish the merit of the KC method and analysis. As the KC methods are applied to the limited data set, the focus should be directed to the strength of the approach and longstanding benefits that can be achieved through repeated applications of the method to subsequent processes. This is perhaps the

legacy of this research effort— method to apply variation risk management techniques to low volume manufacturing processes with limited data availability. Should production volume increase, a renewed investigation can build upon the methods presented here for a more quantifiable outcome.

The case study of QP focuses on just one of the many manufacturing processes used at the Automated Frame and Cylinder Fabrication facility (AFC). This case study begins with a review of the existing AFC processes, the accuracy control measurements and methods, and a discussion of the significance of the hull circularity metric. The data collection and analysis is then presented in a summary format. The data is contained in a separate volume to ensure proprietary information is not compromised. With that in mind, the real numbers are NOT the same as those included in this research document. The content of this report accurately presents the relative relationships of all information but the values are skewed by the author. After the data collection section, the KC methods are applied in the specific context of the modular submarine hull manufacturing practices at QP. Finally, the data and KC methods are summarized to provide a lasting understanding of how future efforts may benefit. Subsequent sections of this research then relate an alternative industry review to highlight the similarities to the aircraft fuselage joining processes of Boeing.

3.2 *Current Process and Nomenclature*

Since many of the procedures and processes used at QP are specific to that facility or to submarines in general, many may be unfamiliar with the terminology used. Before detailing the existing processes, a brief discussion is presented to familiarize the reader with the nomenclature.

3.2.1 Terminology

This section is structured to lead the reader through the terminology and processes as the material and subassembly components progress through the manufacturing process. The terms are very general in nature and are referred to differently in many industrial settings.

Plate Stock—this is the raw material from which all components are constructed. The steel plate arrives at QP from suppliers. These suppliers deliver the associated certifications and material control documentation that proves the material meets the necessary quality standards. The plate stock varies in sheet size and thickness depending on the application for which it will be utilized.

Burning and Beveling—these terms refer to the process of shaping the plate stock into the appropriate geometry. Burning the plate refers to cutting the raw stock into the desired shape. Beveling is performed on the edges of the burned shape to prepare for the subsequent welding operations. Without further detail, the beveling process is necessary to form the proper root gap for a weld bead.

Forming—is the process of altering the geometry of the flat shapes by adding curvature. This is accomplished in a rolling and stamping process that transforms flat components into curved steel components.

Frame—the internal stiffeners of the shell which add strength to the completed hull section. They are T-beam elements that are welded to the inside of the shell plate. Each frame consists of several components that are assembled into a completed circle and inserted into the shell. These components consist of webs and flanges.

> Webs—are the "vertical portion of the T" which are welded inside the shell to form a ring-stiffened cylinder.

Flanges—are the "top of the T" which add structural strength to the web.

Shell—the outer portion of the hull. When assembled into a cylindrical section, they create the "steel tube" of the submarine. The shell is further classified into rings and sections.

Ring—refers to a completed cylindrical shell section that will have frames internally welded.

Section—is an assembly of rings, typically 3 rings per section. The sections are then joined longitudinally together. A completed submarine hull consists of several longitudinal sections which are made up of several rings each.

Fixture—refers to the various types of fabrication jigs and fixtures that facilitate the alignment of various subassemblies for manufacturing. The specific attributes of each type of fixture is discussed as part of the current process review below.

3.2.2 Submarine Hull Component Diagram

Having discussed the terminology, it is helpful to view a diagram of the submarine hull construction sequence. The details for this process are presented in subsequent portions of this effort, but Figure 8 clarifies the nomenclature pictorially[9].

[9] To avoid potential conflict, the names of the processes and fixtures have been changed from those actually used at the Quonset Point facility.

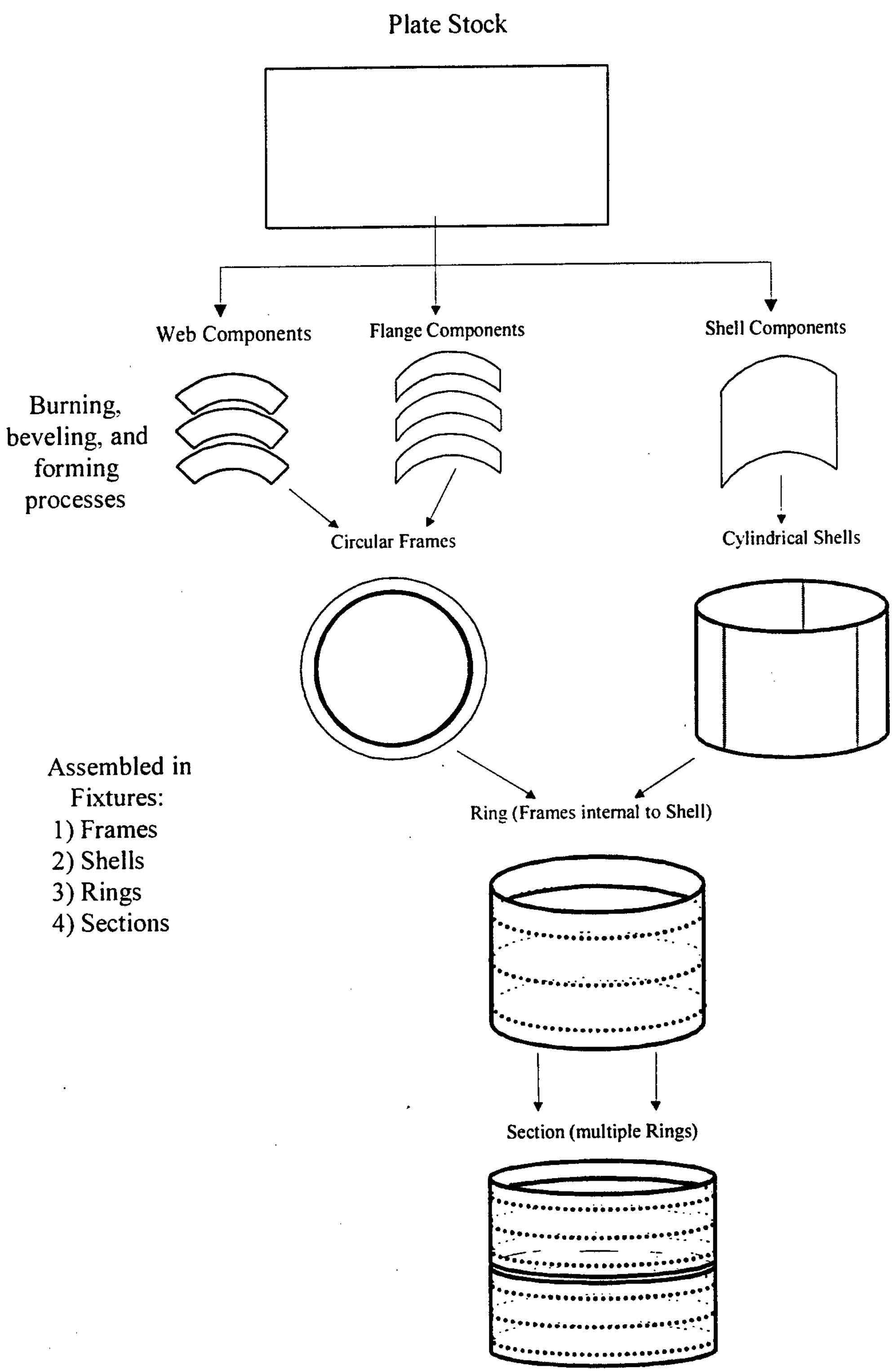

Figure 8: Submarine Hull Components

3.2.3 Current Accuracy Control Practices

The current accuracy control practices employed at QP include inspection, in-process adjustments including datum transfers, and cut to fit. These methods stem from the extensive use of previous experience and vast amounts of in-process dimensional checks. The sound engineering methods of numerous measurements, tolerance checks, inspections and photogrammetry[10], result in a methodical and exhaustive system of checks, adjustments, rechecks, further assembly, and more checks. The resulting product at the end of the production line is a satisfactory submarine hull that meets or exceeds the specifications placed on the system. These specifications are predetermined by the ship designers and engineers and cover such features as alignment, dimensions, and geometric constraints. While these specifications are in part a major motivation for the methods of maintaining accuracy control in submarine hull production, they are only discussed in qualitative terms for this thesis. Again, for reasons of classification and company specific proprietary practices, only the interaction of specifications and processes is addressed.

The sole purpose of so many redundant in-process measurements is to ensure, with an extremely high degree of confidence, that the finished product is satisfactory. Though the costs of so many accuracy control techniques is substantial in terms of measurement time; temporary delay in fabrication while the data is collected and reviewed; and labor effort to analyze and document the inspection, the risks of not satisfying the design specifications are even more significant. In simple terms, the "cost" of a "failure" is so great that it is wholly unacceptable. Unlike the paperclip example in the previous section, a submarine hull section cannot be discarded at the end on the line! The challenge with submarine hull manufacturing, however, unlike paperclips, it that the processes and capital investments are several orders of

[10] Photogrammetry is, broadly speaking, an inspection method of taking "pictures" of an in-process component and comparing the photo with the desired geometry and alignment. This technique requires skilled technicians and calibrated equipment. This research effort does not, however, detail the exact nature of the photogrammetry process for classification and proprietary issues.

magnitude more complicated and costly. In addition, the production volume is many many more orders of magnitude less. In other words, accuracy control techniques currently employed by QP seek to bridge the learning gap that higher volume production would present while simultaneously delivering acceptable quality in the finished product. The question then surfaces: What is the optimal level of accuracy control for low rate submarine construction?[11] To begin to answer this question, the existing manufacturing process must be understood.

3.2.4 Current Manufacturing Process

The ensuing discussion focus on the ring, frame and cylinder manufacturing process rather than the subsequent outfitting and furnishing if the completed hull sections. The order of the discussion, as in Figure 8, follows the manufacturing steps and accuracy control methods as the submarine hull production progresses from plate stock to completed hull sections. The details presented here establish the framework for further data collection and analysis.

Shaping and Forming: The inventory of accepted raw sheet stock begins as large flat sheets of steel. The stock is first cut into the necessary geometric configuration for subsequent fabrication. The various parts include frames—recall that frames are made from webs and flanges—and shells. Each frame consists of several web subassemblies and several flange portions. Due to their size, shells are built up from multiple curved subassemblies of shaped steel, rather than one piece rolled into a cylinder. The shaping process prepares the web pieces by burning to size then beveling their edges for welding (Figure 9).

[11] As an aside, this was the initial question raised and the nucleus for this thesis project.

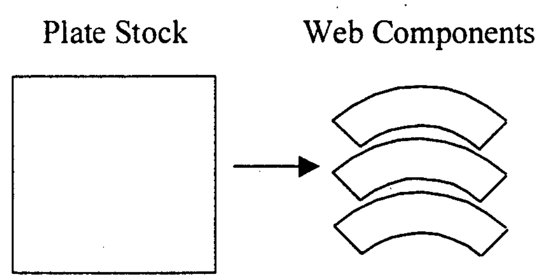

Figure 9: Web subassembly process

The flanges are first burned into strips, beveled on some edges, then shaped to add curvature (Figure 10). This sequence allows better processing control and increased efficiency. After forming, the final size of the flanges are created by burning and beveling the final edges.

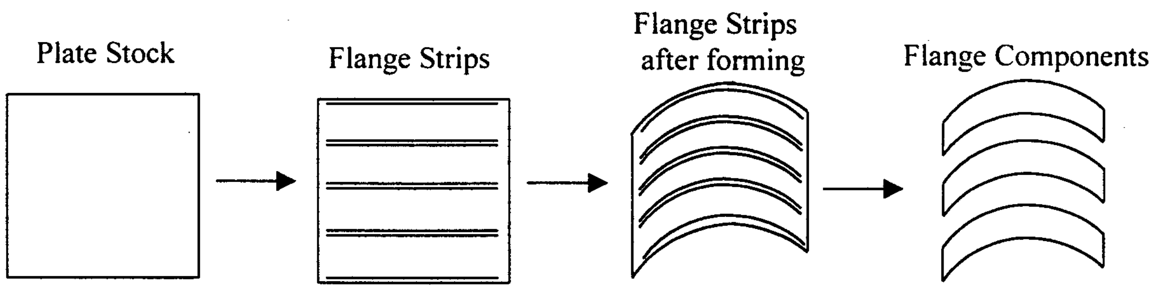

Figure 10: Flange subassembly process

The accuracy control practices during these manufacturing steps include measuring the final geometry of the subassemblies and ensuring they are within the specified tolerance. Such features as flange width, web depth, web arc length and inner and outer cord lengths, and others are measured and recorded. Due to the irregularity of material shrinkage during the welding processes that follow, the parts are not cut to fit at this stage. Rather one component is sized a few inches longer and trimmed to fit during assembly in the fixtures. This is illustrated in Figure 11.

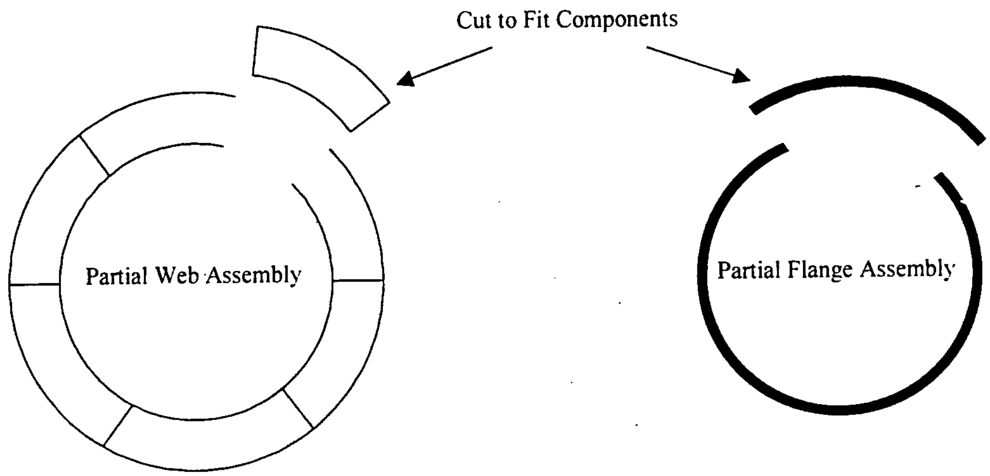

Figure 11: Web and Flange Cut to Fit Illustration

In addition to the frame shaping processes, the shell plate is also sized from the raw plate stock and formed into the curved shell components as shown in Figure 12.

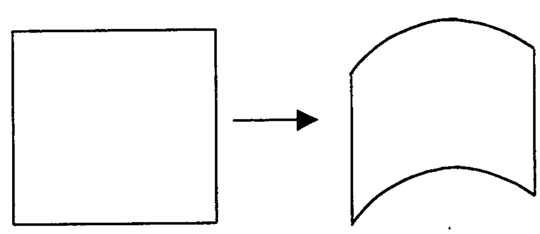

Figure 12: Shell subassembly process

The plate stock is initially beveled on three edges then formed to the desired hull curvature. Accuracy control operations include the geometric size and several dimensional checks to determine if there is any "twist" in the plate. This is determined by measuring both the curvature and verticality of the shell plate. The curvature is necessary to meet the final outside diameter and circularity of the finished hull section. Verticality refers to lines marked on the plate stock before forming. After the forming process, these lines must be oriented along the

longitudinal axis of the submarine hull. Deviation from vertical could result in fabrication difficulties in the subsequent ring and section fixture assembly processes.

Much of the success in this portion of the manufacturing process depends on the tooling alignment and the initial plate condition. If the plate stock enters the forming tools in a flat condition and is aligned properly, then the resulting shell component tends to be much closer to nominal design specifications.

A computer program to check the shape of the shell sections was developed by QP to help determine the optimal root gap between shell components when these components are aligned for welding in the shell fixture (discussed below). For both frames and shells, the series of individual components are "kitted" together before proceeding to the fixtures. The fixtures provide the necessary spatial orientation for numerous subassemblies to allow joining the pieces into completed frames and shells. The logic behind the "kits" is to provide another system of process control by optimizing the subsequent assembly processes. Instead of a random assortment of various piece and components being sent to the next fixture, the components are matched by common characteristics. Although all parts would be within the design tolerance, each possesses some amount of variation and the kit procedure allows an added level of control over the subassemblies. Each kit is constructed of several pieces that the operators group according to the final size and geometry of each component when all shaping and forming processes are complete. By grouping subassemblies together, more consistency results in follow-on production processes.

The following example and figure illustrates this point. If a frame web depth had a design value of d, with acceptable tolerance band of $d\text{-}3\sigma$ to $d+3\sigma$, then several web components are combined so that they are most readily fixtured and welded in subsequent steps. In other words, assume three frames were to be manufactured at this depth, each consisting of four web components to complete a frame, and the

twelve components had the following width dimensions: $d+2\sigma$, $d+\sigma$, $d-\sigma$, $d+2\sigma$, $d+\sigma$, $d-\sigma$, $d-\sigma$, $d+2\sigma$, $d+\sigma$, $d+\sigma$, $d-\sigma$, $d+2\sigma$. The in-process accuracy control practices and operator experience would group these components into three groups as follows: one group with the four $d-\sigma$ components, another with four $d+\sigma$ components, and the final kit with the $d+2\sigma$ pieces. Figure 13 illustrates this process with greatly exaggerated variation for visual recognition.

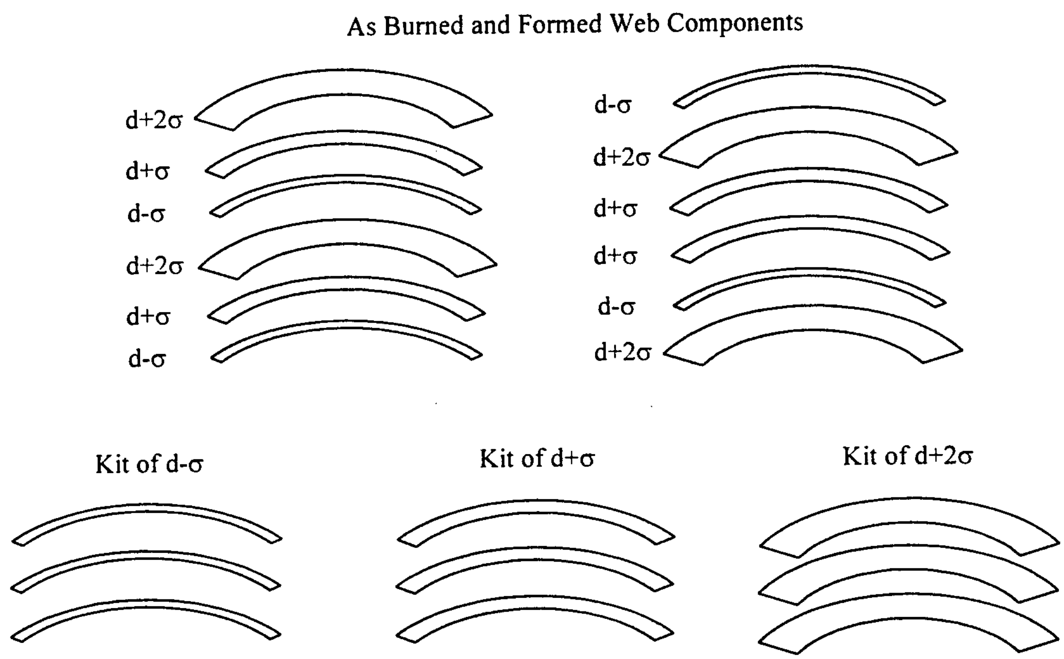

Figure 13: In-Process Component Selection

The shell kits are more complicated in that in addition to the component sizes, they also specify root gap sizes at both ends of the weld to make sure the resulting shell ring is of the proper overall diameter and shape. In either case, frames or shells, the proactive pairing of components is made possible because of the in-process measurements as part of the accuracy control practices by QP's technicians.

Frame Fixture[12]: Once the frame web and flange components are kitted together they can begin assembly into a finished circular frame. This is accomplished with extensive tooling and fixtures.. These fixtures position the flange subassemblies into a circular ring and allow semi-automatic welding. The webs are also positioned within the fixture and welded. The flange ring and web ring are then positioned perpendicular to each other and welded.

The accuracy control methods associated with the frame fixture are graphically presented in Figure 14. They include preliminary fixture alignments and settings, verification of same, at tack and final circularity measurements, and overall diameter measurements. Though these accuracy control practices are particular to the frame fixture and are not intended to represent the complete list of in-process measurements, similar practices are employed in other fixtures. A more detailed discussion of the essential measurements is presented in section 3.3.1.

[12] Since the focus of this research is on the accuracy control and KC methods, only a concise overview is presented. This short description does not do justice to the enormity and complexity of these fixtures as well as those that follow. These machines are marvels of engineering in their own right and they require highly skilled and experienced operators. Without these skilled craftsman the fixtures alone cannot produce a modern nuclear submarine hull.

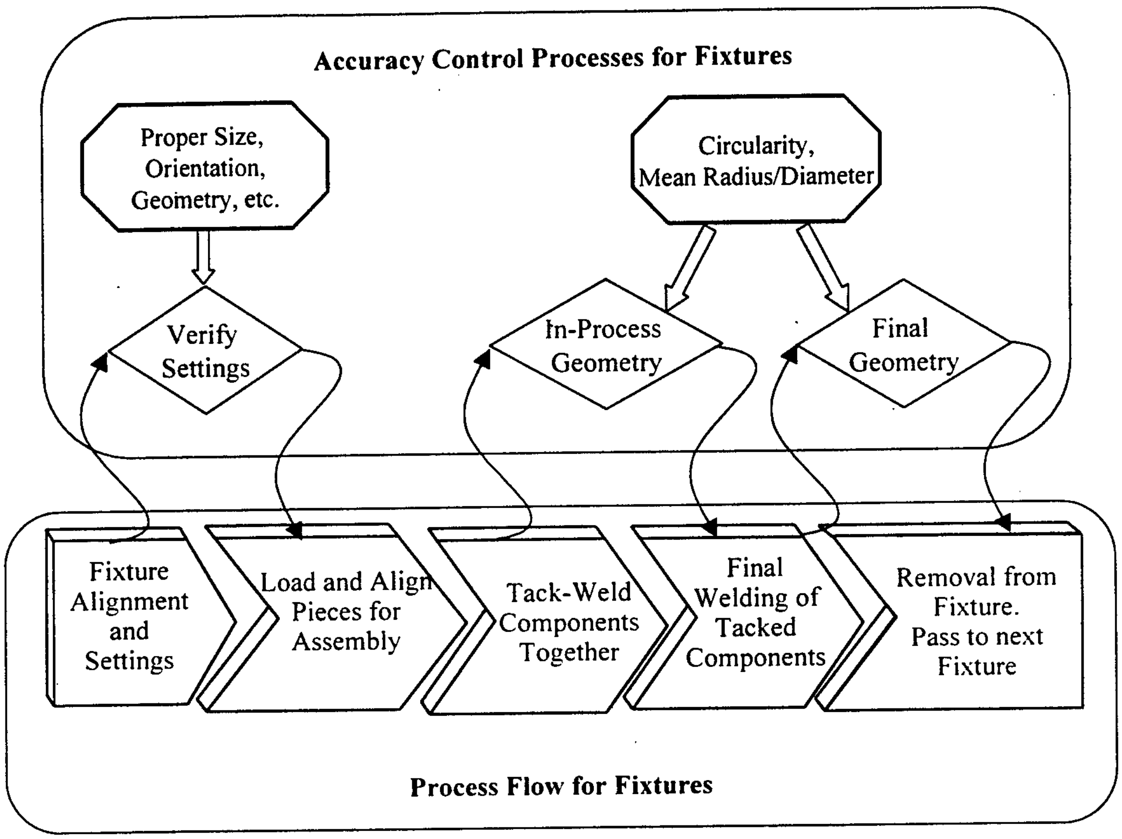

Figure 14: Fixture Process Flow and Accuracy Control Measurements

A frame resembles a circular T-beam with an internal flange, as illustrated in Figure 15.. The outer circumference will already have a beveled edge for welding into a circular shell ring from operations highlighted in the previous section.

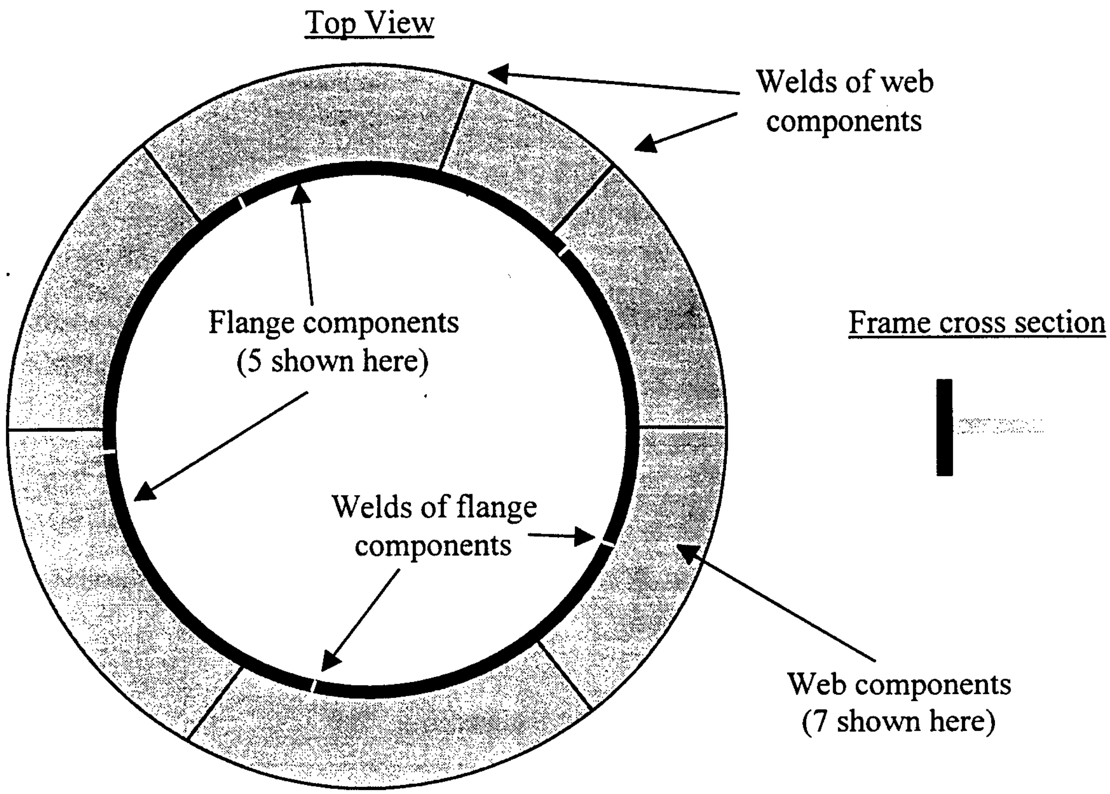

Figure 15: Completed Circular Frame

In these discussions, "at tack," refers to an in-process condition where the individual components are aligned with each other using the appropriate fixture. They are then welded together with small weld beads to hold their position. The in-process accuracy control measurement allows the built up assembly to be re-verified to meet the design tolerances before committing to final welding. If the assembly is found in error, adjustments are made at this stage in the manufacturing cycle while the parts are still somewhat independent and capable of being realigned. Once the in-process accuracy control analysis determines that the assembly is acceptable, the full penetration final welding is conducted and the assembly re-checked before proceeding to the next fixture. This need for final measurement is a result of the uncertainties involved in component distortion during the welding process. Although the fixture uses substantial means to hold the proper shape of the assembly, the heat

input during welding can cause an assembly which was satisfactory at tack to become unacceptable in the final stage. The operator's experience with the "art" of welding dramatically impacts this outcome and is outside the control of any SPC methodology. As QP has learned over many years of submarine hull fabrication and illustrated in the data collection which follows, however, as long as adjustments are made in the at tack condition, the final product is most often acceptable.

<u>Shell Fixture</u>: As in the frame fixture above, the shell fixture receives a number of shell components and facilitates the construction of a cylindrical shell, which is the actual outside pressure hull of the completed submarine. Though substantially similar in function to the frame fixture, the shell fixture requires a different set of operators and practices. In the shell fixtures, the shell components are loaded vertically into position and aligned relative to each other to produce the proper finished hull diameter. Part of this alignment, mentioned in the earlier discussion on shell components, entails the proper vertical root gap between the individual components. The resulting assembly from this manufacturing process is a cylindrical shell at the designed outer diameter. The final shell assemblies are shown in Figure 16.

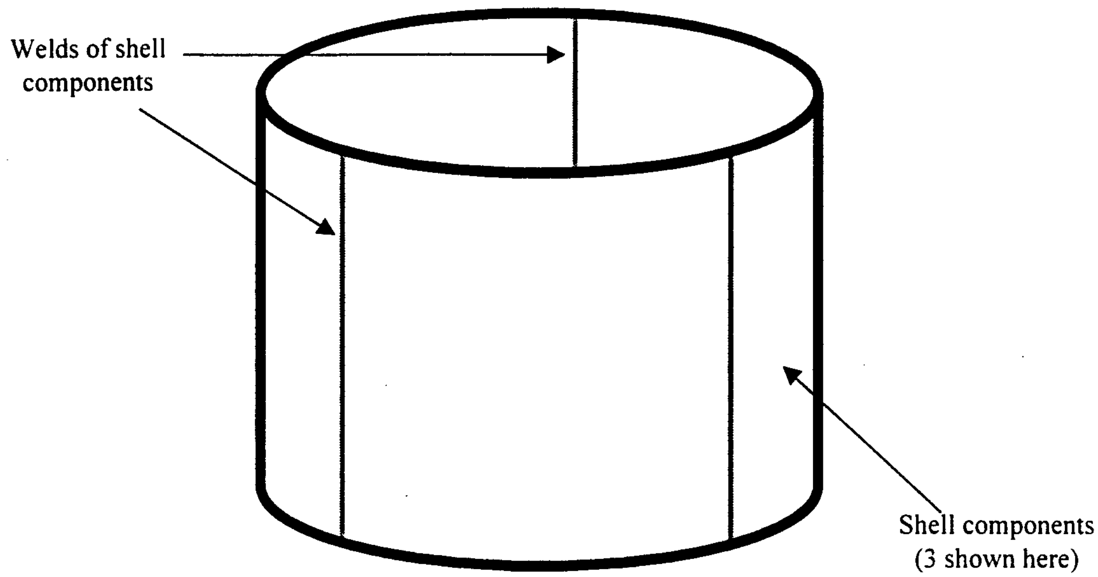

Figure 16: Completed Cylindrical Shell

Part of the shell fixture process must accommodate the shrinkage which results from the next fixture, where the frames are joined with the shell. As such, many accuracy control functions are performed at this stage of construction that allow for future fabrication. These include layout of horizontal reference lines to identify the location the internal frames for the next fabrication process. Though not specifically included in the data analysis, the proper alignment of the frames is predicated on the layout marks created here. In addition, since the shell is a vertical cylinder at this point, there is ready access into the structure for layout markings. As manufacturing continues beyond this fixture, the submarine hull sections become ever more cluttered with frames, tank foundations, piping, and equipment. The layout performed by the accuracy control personnel here is eventually rechecked and, if necessary, adjusted before such items are welded into the hull. The lack of interference in an empty shell is a fortuitous opportunity to perform an initial reference layout.

Ring Fixture: The completed frames and shells are brought together in the ring fixture. In this fixture, the welded outer diameter of the submarine hull—the shell—is aligned to receive the internal stiffener "beam" of the hull—the frames. This is accomplished by again orienting the shell such that the longitudinal axis of the submarine is vertical. Frames are then lowered into the shell from the bottom-up and tack welded into position. It should be obvious at this point that the need for accuracy control in frames and shells was essential—the frames have to fit within the shells. The frames are rigid steel T-beams with an outer dimension and circular geometry. The shells, though also of steel, have a fixed circumference but can be manipulated to some degree to form a perfect circular cross section, or a slightly "indented" circle. This is a critical step in the submarine hull manufacturing process.

The structural integrity of a ring stiffened cylinder under the force of external pressure (i.e., a submerged submarine operating at a deep depth) is in a large part dependent upon the geometry of the hull. A perfectly circular cylindrical cross section is the strongest since hull compressive forces are uniformly distributed throughout the hull. If the shape deviates from a perfect circle, stress concentrations result. This fact of physics is accounted for in the design process and in the specifications for the nominal design tolerances for the shape of the hull. The designers incorporate an added degree of overdesign in the structural elements of the hull to account for an accepted amount of out-of-roundedness. The manufacturing processes seek to minimize the deviation from circularity but must also fit the assemblies together. Though far from the physical act of fitting a round peg into a square hole, the analogy is applicable. The frames are the round pegs, but sometimes they are not perfectly round. The shells are, up to the point of welding the frames into the hull, round holes which are not perfectly round. The frames are designed such that they fit inside the shell with the desired root gap around the frame's circumference for welding. This "fit" is shown in Figure 17 for both the design case and an extreme example with substantial deviation from nominal.

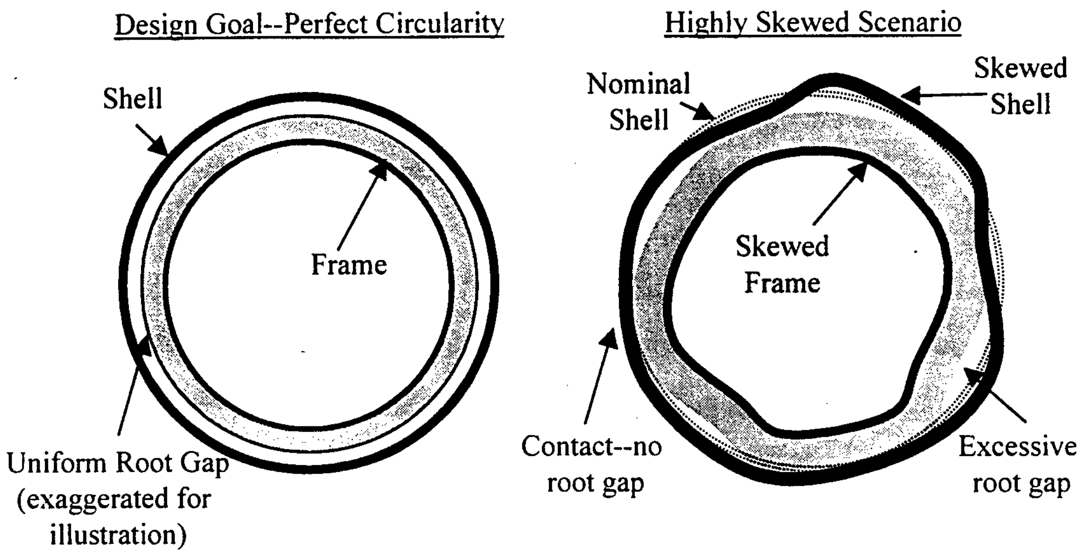

Figure 17: Ring Geometry Illustration—Design versus Extreme

This illustration does not highlight the multiple characteristics that must be simultaneously satisfied in the ring assembly process. Once inserted into the shell assembly in the ring fixture, the frame and shell must interact in such a way that: 1) the frames actually fit into the shell; 2) the root gap allows welding of the frame into the shell; 3) the proper frame alignment with respect to the longitudinal position within the shell is maintained; 4) the circularity of the finished ring meets design specifications; 5) the overall frame-to-shell web depth satisfies the design dimensions; and 6) the overall ring forward and after ends meet to their respective leading and trailing rings to allow achievable build up into a larger assembly—a hull section.

Many of these design parameters compete against one another and add considerable complexity to the manufacturing process. To ensure a satisfactory outcome, accuracy control techniques are employed. Perhaps most important are the measures taken in the previous fabrication processes—frame fixture and shell fixture. This information limits the variation in the ring assembly process by mere virtue of satisfying preliminary tolerances before passing down stream in the production process. These

accuracy control practices reduce the risk of progressing to a ring fixture with incompatible frames and shells. Another essential part of the current accuracy control practice is the historical experience with ring fabrication. The skilled fixture technicians, by working over many years, have developed the necessary knowledge to understand which adjustments can be made for the various types of design specifications. Making in-process adjustments as necessary to each particular frame and shell interface, though sometimes time consuming and costly, is the alternative to downstream component rejection and even greater costs.

Section Fixture: The final fixture combines multiple ring assemblies into larger hull sections. The section fixture aligns ring assemblies and welds them together around the circumference of the hull. The alignment relies upon some of the level reference lines first initiated in the shell fixture as well as additional accuracy control data obtained as a result of subsequent frame insertion in the ring fixture. As in the previous fixtures, the hull circularity is again a critical design parameter that must be controlled in the manufacturing process. Prior to completing the significant welds which become part of the exterior submarine pressure hull, at tack measurements are taken to ensure proper alignment.

The rings are joined with horizontal welds as the rings are positioned with the longitudinal axis of the submarine in the vertical position. Figure 18 shows the orientation of the completed section. As was the case for the ring fixture processes, the perfect circular cross section rarely occurs in the ring-to-ring weld. Therefore, the section fixtures use an extensive series of clamps and forms to align the seam for at tack welding and circularity accuracy control verification. These same devices are used in the final section welding as well. The finished assembly is again measured to ensure the final circularity is acceptable.

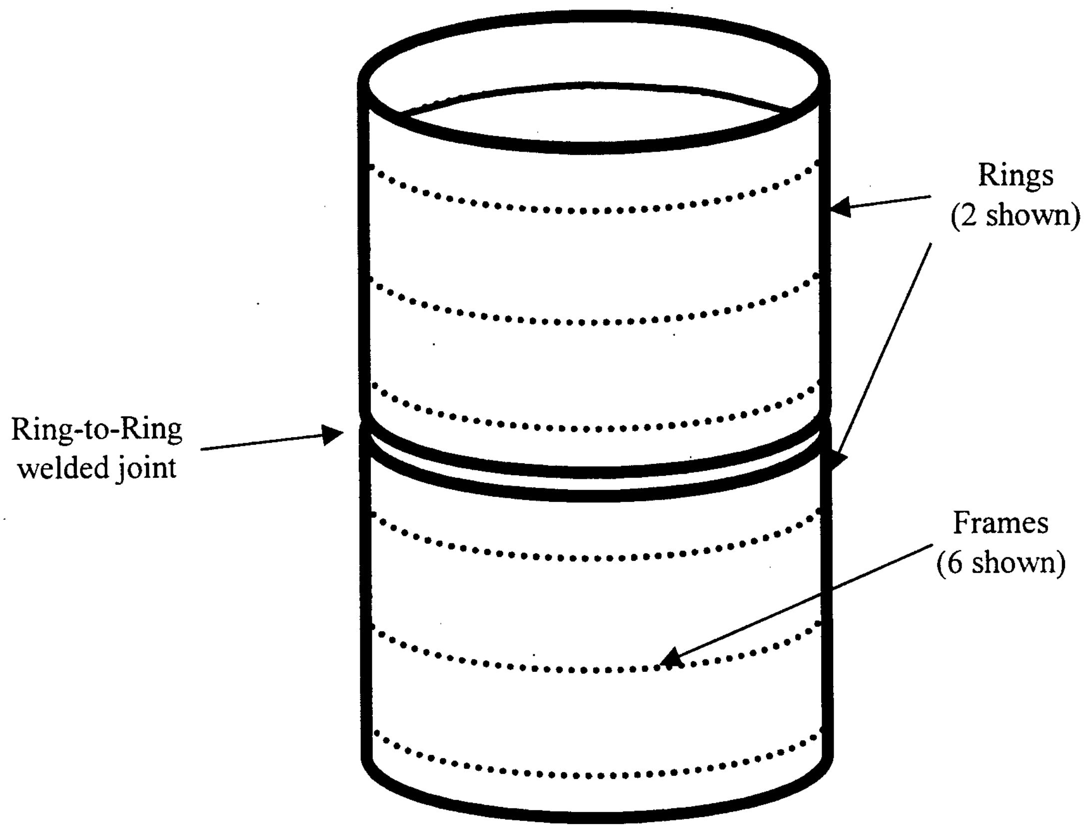

Figure 18: Completed Hull Section

From this stage the submarine hull section can be outfitted with the necessary pipes, tanks, and equipment as it progresses from a ring stiffened cylindrical steel tube towards a crowded array of cables, pipes, and gear[13]. It is at the completion of the section assembly that this research ends. The remainder of the intricate and interesting submarine construction process is left for others to explore. Focus is now directed at the application of the KC methodology to the above processes and subsequent analysis.

[13] As amplifying information, much of the outfitting of the completed hull section is also performed at the Quonset Point facility before it is transported to Groton, CT for final construction and section-to-section joining.

3.3 *Application of the KC Method*

At this point, the reader has been presented with an overview of the KC methodology; as well as an overview of the major processes, techniques, issues, terminology, and concerns encountered in submarine hull construction. Attention is now directed towards identifying one or two key areas for detailed investigation. The area chosen for this analysis was the hull form circularity requirement. The process-to-and-from-design (PTFD) KC method is applied to the manufacturing practices at the Quonset Point facility.

The structure for this investigation follows the same KC phases discussed at length above—identification, assessment, and mitigation. First, the PTFD KC method is illustrated as a case study for QP. This method identifies essential characteristics that impact the fabrication process through multiple subassembly processes and finally the quality of the end product. The processes and accuracy control practices are then investigated to assess the impact of one particular KC. This case study limits the analysis to one *key* in an effort to demonstrate the PTFD method and contain the scope of the project. Finally, some conclusions are drawn from the KC analysis and variation risk mitigating practices suggested.

Throughout this section, as previously stated, one of the concerns in writing an unclassified thesis involving such sensitive practices as submarine hull construction, is the issue of discussing confidential or proprietary information and practices. To address both of these issues, the author has changed much of the nomenclature and omitted certain practices. In addition, since a portion of this section involves data collection and analysis, all of the data are disguised from the real values. Further, only the data analysis is included versus the raw data. These actions in no way limit the usefulness of the work or the validity of the conclusions, instead they are a stated

as a matter of fact at the onset to avoid any potential conflict, even before data collection begins.

3.3.1 KC Identification

To begin the analysis, several plant visits were conducted. The initial purpose of the visits was to refine the preliminary problem statement into a manageable thesis project. In addition, these plant trips helped the author understand the processes involved and the design specifications being fulfilled. This was accomplished by walking the production sequence from the plate stock, to burning and beveling, onto forming, and into various fixtures. While this was done with the focus of *process-to-design*, the opposite direction of PTFD KC method began to investigate the performance and design specifications established at the final section level and trace the variation towards the upstream processes.

Thus, the two investigative techniques used to understand the QP processes and identify essential characteristic traced in two distinct paths. The entering hypothesis anticipated a convergence towards some common KCs. Specifically, in the context of the methodology suggested here, the flows were:

1. *Process-to-design* in the form of plant operations; fixture control; operator involvement; process capability, repeatability, and sensitivity; material movement; and datum transfers.

   How did the process characteristics impact variation risk in the nominal design product?

2. *Process-from-design* in the form of design specifications; in-process inspections; accuracy control practices; and customer acceptance criteria for the completed submarine hull sections.

How did the product characteristics impact variation risk in supporting processes?

To bound the scope of this project, several simplifying assumptions were made. The first was to limit the endpoints of analysis. The analysis begins at the first plate burning process for shells or frames. The evaluation ends at the section fixtures where rings are joined together. The PTFD KC identification process traces the plate stock through the section fixture in the process-to-design flowdown; and traces section design characteristics backwards to the plate stock. Each flowdown method is described below. The reader is reminded to refer to section 3.2 for process descriptions.

Process-to-design: The plate burning and beveling processes focus on component geometry. The individual components are sized to allow for shrinkage during the subsequent welding evolutions. The accuracy control checks on the frame webs include web depth at various radial locations, chord length, overall outer circumference total arc length, and others. The frame flanges are checked for width, curvature, and arc length. The shell components are initially checked for flatness, then sized and three edges beveled. Layout lines are marked and verified, then the plate material is formed. The forming process is intended to develop the correct shell curvature without skewing the plates. In other words, the desired shell component has a single degree of curvature. To ensure this single degree of curvature, the verticality of the formed plate is verified and datum control marks added to track the condition of the component as it proceeds through the manufacturing process. Though the shell components are massive rigid steel shapes, they are handled throughout the fabrication process to maintain the intended curvature. They are stored on edge with the longitudinal axis of the submarine in the vertical position. If they were stowed horizontally, similar to a rocking chair, then the weight of the steel tends to distort the formed shape.

The frame and shell components are then moved to the frame and shell fixtures, respectively. The fixtures are first adjusted and set-up in the proper orientation for the desired subassembly characteristics. The settings are recorded and verified to ensure proper configuration. QP's accuracy control practices also record the particular fixture involved in the process to provide a traceable record of the assembly process. Once the fixtures are configured, the individual components are loaded and arranged for welding. The arrangement mechanisms include substantial hydraulic positioning devices to hold the components in the proper geometry for welding. The geometry of concern in both frame and shell fixtures includes the circularity of the resulting subassemblies. In addition, the frame dimensions and shell transverse orientations are checked.

The ring fixture combines the internal frames with the shell subassemblies. As with prior fixtures, the ring devices are first adjusted for the proper component sizes. The shell is loaded into the fixture and individual frames fitted inside. The alignment of the frames is done according to the geometry specified by the design. Frames are then down hand welded with semi-automated welding. More frames are added depending on the particular hull ring being fabricated. The entire ring assembly—consisting of multiple frames and the shell—is then rotated vertically to complete the welding on the other side of the frame to shell root gap. Accuracy control checks are performed at tack and final weld condition for circularity, horizontal alignment of the frames (i.e., perpendicular to the longitudinal axis of the submarine hull), and overall frame depth.

The final fabrication process combines multiple ring components longitudinally into a hull section. The alignment of ring sections is facilitated by hydraulic mechanisms and level supports. The ring to ring root gap must account for the level characteristics of each ring independently as well as the combined assembly. The completed section

accuracy control measurements include circularity, to ensure the welding does not distort the ring elements when combined. The KC flow for the process, part, sub-system, and product KCs are indicated in Figure 19.

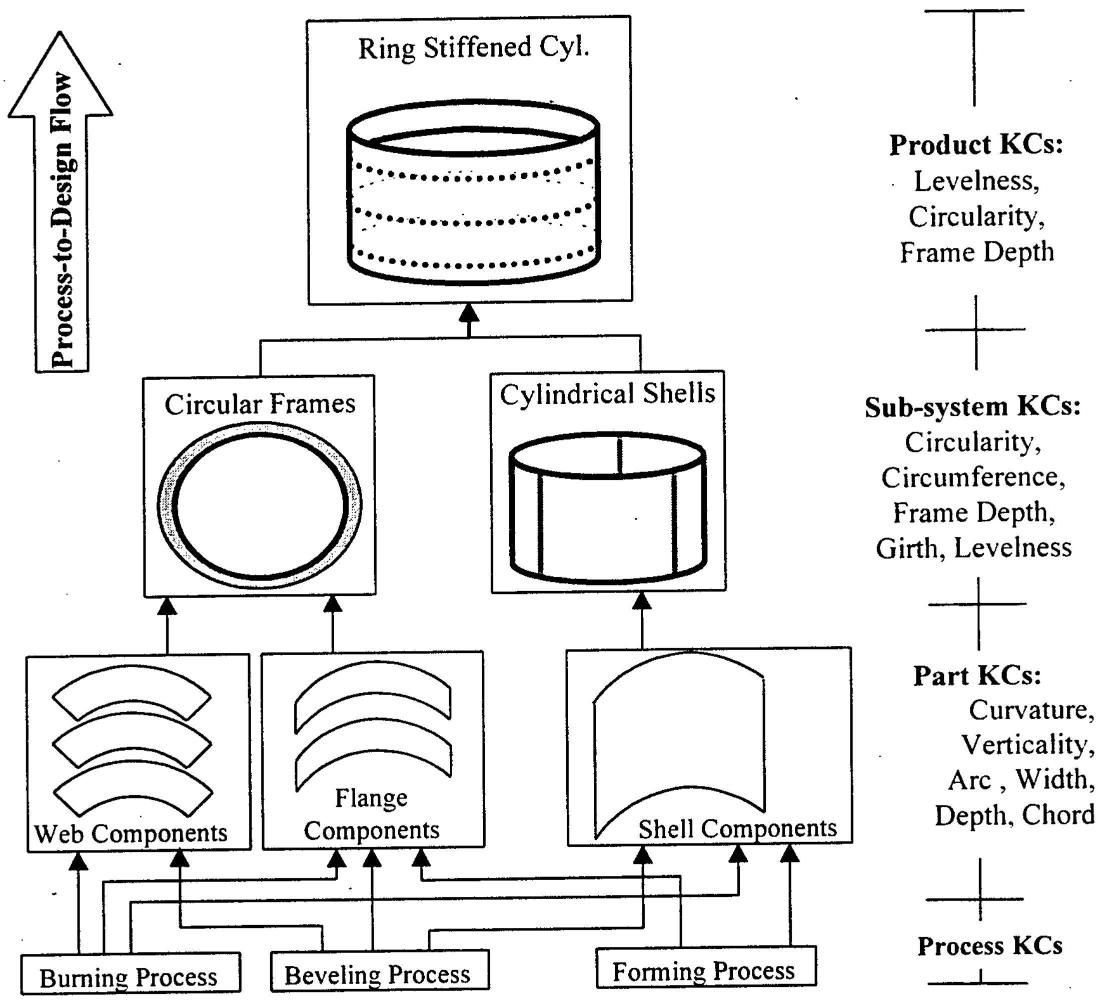

Figure 19: Process-to-Design KC Flowdown

A summary of potential KCs identified in the process-to-design PTFD KC method is summarized in Table 2. The potential KCs which appear to have a significant influence on the final product design, in this case the hull section, are included. These KCs are not, nor should they be in the PTFD method, an all-inclusive list of every possible cause and effect link between process and design. Instead, they

embody the elements identified during the KC investigation of tracing the process and component interactions through the fabrication sequence towards the end product.

Table 2: Potential Process-to-Design Key Characteristics

Element or subassembly	**Potential Key Characteristic(s)**
Frame: Web	Depth Chord dimension Arc length
Frame: Flange	Width Curvature Arc length
Shell	Curvature Verticality
Frame Fixture	Circularity Circumference Frame depth
Shell Fixture	Levelness Girth Dimension Circularity
Ring Fixture	Levelness Circularity Frame depth
Section Fixture	Levelness Circularity

Process-from-design: Now the PTFD KC flowdown method reverses direction and traces the product parameters backward through the manufacturing evolution from the design requirements to the individual processes. The design specifications for the section, ring, shells, and frames are identified in a comprehensive QP dimensional control document [Zelen, *et al.* 1998]. The internal document identifies over 3000 accuracy control measurement procedures taken to ensure the product is satisfactory. Each of the procedures is further detailed as to precisely the manner in which the accuracy control determination is made. The in-process measurements taken to verify the design requirements vary in complexity and number from simple dimension

checks to complicated photogrammetry methods and inspections. It should be noted that the series of checks mentioned here are only designed to control the dimensional accuracy of the finished product. They are not the only quality measurements and verifications made in the submarine construction process.

For the section design, the accuracy control practices include validation of the shell-to-ring alignment, various centerline orientations, and circularity of the finished product. These measures are required to ensure that the ring subassemblies are aligned properly relative to each other before final welding.

The ring subassembly specifications call for centerline alignment, circularity, girth dimension, and level reference at multiple locations. Specifically, many of the measurements are taken at the location of each frame and the forward and after ends. These, in conjunction with the fixture setup, ensure the individual frames are properly oriented with the shell.

The demands placed on the shell assembly fixture and process include the fixture setup and alignment, overall girth determination, orientation of the shell components and circularity. The shell components themselves are required to satisfy overall arc length and diameter. These determinations are determined for the as welded shell subassembly with the assistance of a computer dimensioning program. The design specifications for the shell plate account for the root gaps and shrinkage that occurs in the shell and ring assembly processes.

The frames are required to satisfy a circularity specification and fixture setup. The former is determined. The individual web and flange accuracy controls are taken to ensure the proper dimensions. The dimensions specified include flange width, inner and outer radii for the frame components; and web depth, arc length and chord

dimension. The PTFD KC flow for the process, part, sub-system, and product KCs are indicated in Figure 20.

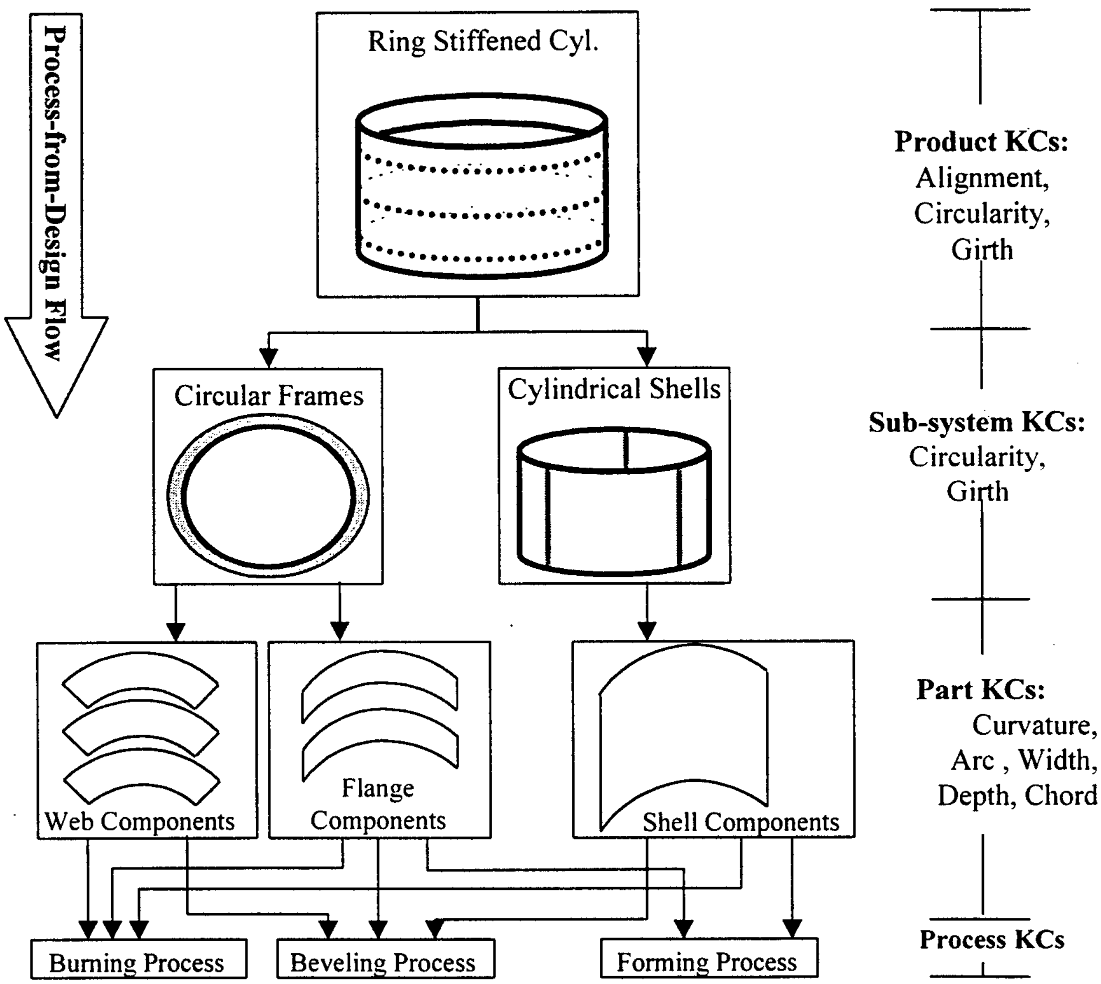

Figure 20: Process-from-Design KC Flowdown

As was the case in the PTFD process-to-design KC flowdown, potential KCs where identified using the design specifications as the starting point. These results are summarized in Table 3.

Table 3: Potential Process-from-Design Key Characteristics

Element or subassembly	**Potential Key Characteristic(s)**
Frame: Web	Depth Chord dimension Arc length
Frame: Flange	Width Arc length
Shell	Arc length[14] Curvature
Frame Fixture	Circularity
Shell Fixture	Girth dimension Circularity
Ring Fixture	Centerline alignment Girth dimension Circularity
Section Fixture	Ring-to ring alignment Circularity Centerline orientation

The benefits of the PTFD KC flowdown method can now be appreciated by combining the potential KCs suggested by both trace methods. The common elements of the *process-to-design* and *process-from-design* flowdowns are presented in Table 4. The PTFD method reduced the potential number of KCs from 19 in the process-to-design investigation and 16 in the process-from-design to 10 common KCs.

[14] The actual design dimensions specify the girth and diameter, versus the arc length and curvature, respectively, because the CYLFAB V2.1f QP computer program assumes the individual shell components are arranged for welding, including root gap, before the dimensions are determined.

Table 4: Modular Submarine Hull Construction Key Characteristics

Element or subassembly	**Key Characteristic(s)**
Frame: Web	Depth Chord dimension Arc length
Frame: Flange	Width Arc length
Shell	Curvature Girth Dimension
Frame Fixture	Circularity
Shell Fixture	Circularity
Ring Fixture	Circularity
Section Fixture	Circularity

Upon further investigation and understanding of the processes involved—facilitated through interviews with the fixture operators, forming personnel, and cutting and beveling manager—more information about the KCs came to light. The existing frame subassembly process contained a step which used a portion of the frame web that was initially cut longer than required and trimmed to fit the final frame dimension. The presence of the extra material added a level of insurance against an undersized frame. The drawback to such an approach to variation risk control is the added cost required to measure, mark, burn, bevel, insert, align, and finally install. The same situation applies to the frame flange lengths as well. As such, both "arc length" KCs and the "chord dimension" web KC were eliminated from further analysis. They still exist however, and represent primary targets of opportunity for procedural change if the remaining processes can support the tighter variation tolerances. This will be addressed in the final section of this case analysis.

Of the remaining seven common KCs, the circularity KC will be used as the quantitative parameter to evaluate for the submarine hull construction process. The rationale is based partly on the overwhelming commonality of this KC in four of the seven processes or evolutions; and partly because of the availability of data.

3.3.2 Data Collection

Data collection for the submarine hull fabrication process is recorded in reams upon reams of paper. The collection procedure first identified the information that was desired—information relevant to the circularity KC—then proceeded to acquire a complete data set. In that the analysis was based on a partially completed hull, not all data was available at the time of collection. In addition, since the submarine hull production rate is less than one hull per year, the quantity of information is severely limited—when compared to the extremely high volume paperclip example used earlier. With this perspective in mind, data was obtained, organized into a spreadsheet for manipulation, and analysis begun.

3.3.3 Variation Risk Assessment and Data Analysis

The next phase of any KC method is to assess the impact of variation in the identified KCs. In section 2.1.2, Taguchi's Quality Loss Function and the variation budget methods were presented as mathematical means to assess the impact of variation. The quantitative assessment requires detailed knowledge of the quality loss or statistically significant SPC data. In the case of the data collected for the submarine hull fabrication, such clearly defined information is lacking. For the same reasons the KC assessment process is a significant challenge for other industries, the quantification of the impact of variation risk is just as problematic for submarine hull fabrication. Notwithstanding the challenge, an earnest attempt was made to determine a quantitative link to variation risk in the circularity KC.

Data was collected for frames, shells, rings and sections for frames X to X+51.[15] The frame data was the most complete since the majority of frames were completed at the time of data collection. The section data was discounted entirely since only three data points for ring-to-ring joins were available. Of the possible 51 data sets to populate an analysis sample, only 25—less than 50%, survive the complete flowdown from frame fixture to ring fixture (again, the section data is no longer considered).

Despite the limited data, there are several important observations that lead to a better understanding of the QP submarine fabrication methods. The variation from designed nominal circularity was determined by calculating the average area gap that exists between the perfect circle at the nominal diameter—the design shape, and the actual frame. The gap calculation accounts for variation from both smaller and larger than nominal diameters. For a visual representation of the area gap variation, refer to the similarly shaped weld root gap shown in Figure 17.

The computation of the undersize or oversize of the as-built frame circularity variation was then normalized to values between 1.0 and –1.0. To illustrate the large variability in the data set, Figure 21 presents the frame by frame variation between the as-built and design condition. Though the variation about nominal design (y-value of zero) is substantial, there is an obvious trend to undersize the frames. The results indicate a mean shift from nominal design dimension of m=0.0—which would correspond to the actual frame size being a perfect circle of nominal dimension such that there was no area gap—to an undersized value of m'=-0.33. The points behave in an approximately normal distribution about the shift. The real values of the data, as opposed to the normalized values presented here, were validated by QP personnel to correspond to their experience. This undersize can be related to the deviation of the mean radius from nominal. The reader is cautioned against making assumptions

[15] Sequential transverse frames starting forward and working aft, not beginning at the bow. The data collection covered only the right cylinder hull portion or those sections closely resembling a right cylinder. Actual frames disguised by the "X" notation.

about the size of the variation in Figure 21. The units are not presented, but the design specifications require circularity tolerances of less than 0.08% of the diameter.

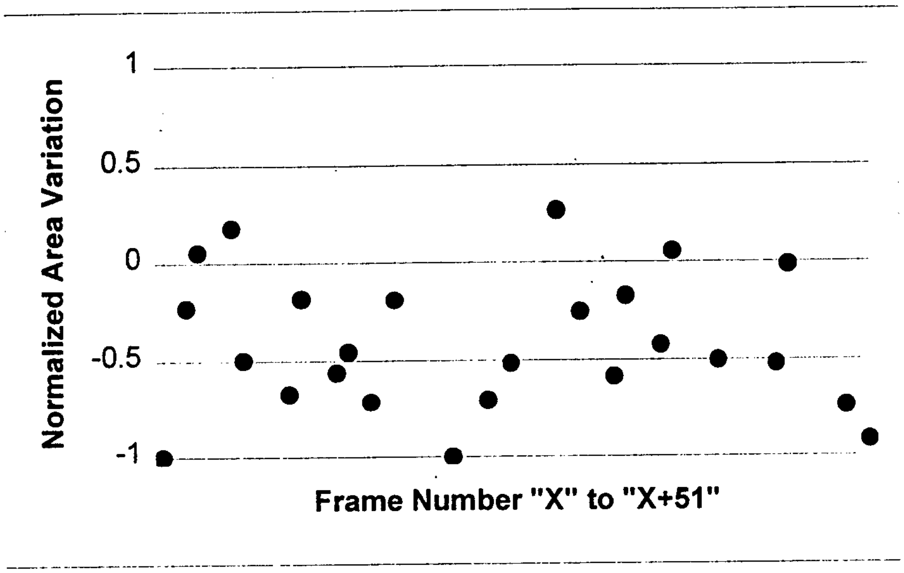

Figure 21: Frame Variation—Average Area Gap Nominal vs. Actual

The frames are usually undersized to allow more flexibility for frame insertion onto the shell at the ring fixture. Only four of the 25 points shown in Figure 21 represent frames that where larger, on average, than the nominal design. About the negative mean shift, only ten points are larger than the average.

The logical next step in assessing the variation risk is to determine the impact of the area gap variation. The frame labor content, in this case representing the percentage of the targeted labor content, was used as a measure of quality loss. The size variation was plotted against the labor content during fabrication of the frame subassembly, Figure 22.

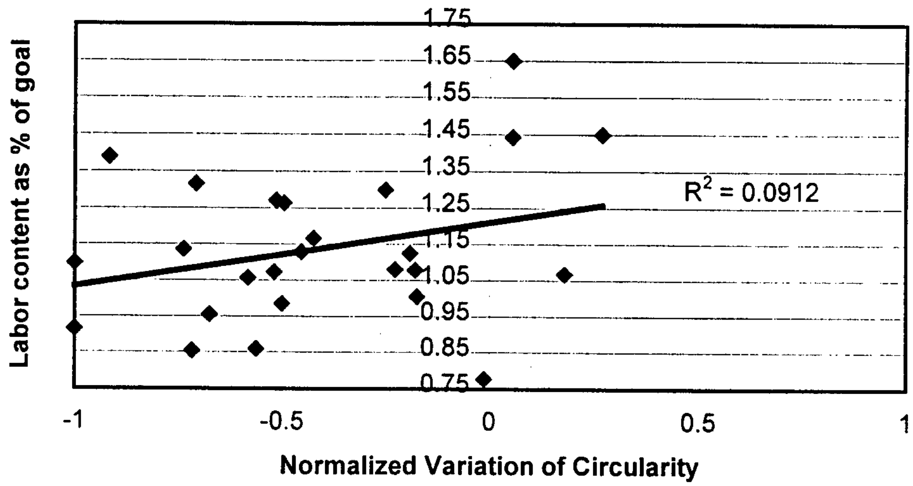

Figure 22: Frame Circularity Variation vs. Labor Content

In this figure, the labor content of 0.75 implies the actual frame fabrication in the frame fixture required 25% less than the labor target for that frame. The data scatter is still significant however, as evidenced by a low coefficient of correlation (R^2) from a linear regression. The data are scattered due to numerous statistical and process effects. For the former, the low rate of production and small sample set for the data collection resulted in a barely tolerable number of points that are not proposed to be statistically significant. As for process, the same issue of low production volume is at the center of the discussion. Labor content is highly varied when compared to the recommended labor target.

The insights from this assessment indicate that the undersized frames (i.e., those points to the left of 0.0 on the horizontal axis, Figure 22) require less labor to fabricate. This is not to say that the small frames are less costly. This broad assumption can only be valid if the labor goal values are consistently set for all frames. The labor content goals are continually adjusted to account for the experience curve of repeated production. The precise mechanism for this adjustment

is outside the scope of this work, but would be instrumental in further developing the quality loss function for the frame circularity KC.

Now that there seems to be an observable undersizing trend for the frames, the next step in the modular hull construction sequence would be to perform a similar analysis for the shells. Again the circularity KC is of foremost interest and again the normalized area gap between actual and nominal is determined. The influencing factors for the KC are plotted against labor in Figure 23. The regression again shows poor data correlation, but an opposite trend towards oversizing. The plot contains only nine data points because of the availability of data. Only two of the shell assemblies are smaller than nominal (i.e., data points to the left of 0.0) in the figure. Though the data set is sparse, the larger shells still suggest less labor content relative to the prescribed goal.

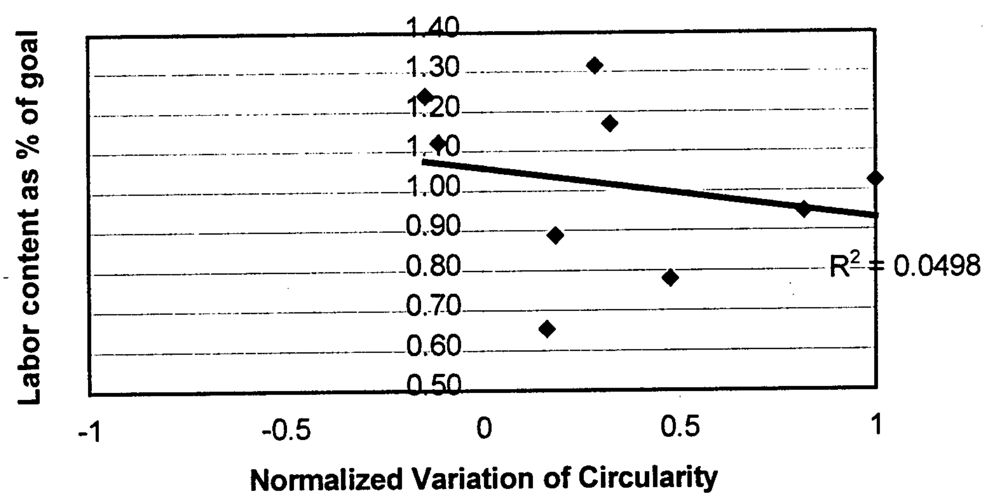

Figure 23: Shell Circularity Variation vs. Labor Content

The final extension of the circularity KC assessment combines both shells and frames into rings (refer to Figure 8 for the illustration of this combination). A priori, Figures 22 and 23 suggest that combining multiple frames from left to right in the first figure,

into the shells moving left to right in the later figure, may result in an offsetting labor content dynamics. Presented another way, the higher labor content shells with normalized variation less than 0.0 in Figure 23 correspond to lower labor content frames, which would be the negative normalized variation of circularity points in Figure 22. When combined as a ring assembly, the counteracting labor content dynamic is expected to offset each other and result in some value in between the two labor content percentage extremes in both figures. This variation behavior should manifest itself as a less significant relationship of labor content versus variation when the frames are combined with the shells into ring subassemblies. The actual results are contained in Figure 24.

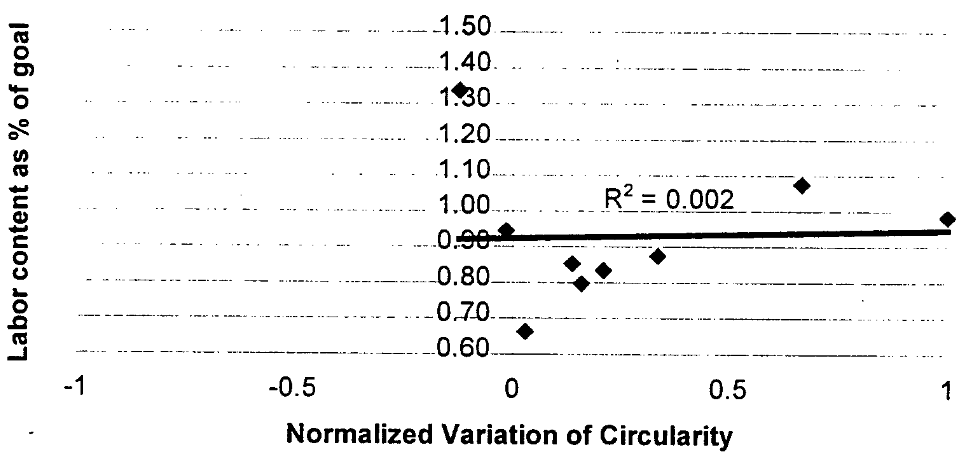

Figure 24: Ring Circularity Variation vs. Labor Content

The rings are once again more often larger than nominal but the labor content seems to be white noise. There is a greater clustering of ring circularities compared to the frame process which loosely suggests intent to arrive at these conditions. The correlation coefficient for the linear regression shows almost no significant relationship between circularity variation and labor content. Labor may just as likely exceeds goal as surpass the desired ring fixture labor target.

This realization highlights the need for further investigation to determine a more methodical quantitative assessment of variation. This less than desirable result was not altogether unexpected, however. During the course of the research, many discussions with the skilled technicians suggested that the different levels of variation might not be explained by the labor content data alone. Since the submarine hull fabrication process is very manpower intensive and involves the art of welding, there is bound to be a large variance in the overall dimensional control between subassemblies. As discussed in the asymmetric quality loss function concept, perhaps the true "cost" for undersized circularity can be applied to the labor content analysis and skewed to favor the larger size. Such would be the case when substantially undersized assemblies would not satisfy the design structural integrity parameter (i.e., generating a step change in the quality loss function for unacceptable components). If this were true and quantifiable, then variation in submarine hull construction process data may be analyzed more methodically.

3.3.4 Variation Risk Mitigation Practices at QP

Section 2.1.3 presented the argument that variation risk mitigation revolves around change. Be it incremental or sweeping change, once variation risk areas are identified and assessed as essential to the ultimate product performance characteristics, the two arenas for change are the processes involved or the design itself. The ongoing accuracy control practices at QP have developed substantially over the years of submarine hull fabrication. The learning experience enables process improvements for existing designs. Though the QP data set is small compared to the mass production efforts observed in the auto, consumer electronic, and even aircraft manufacturing industries, some successful mitigation strategies have been adopted.

At the heart of QP's VRM program are skilled craftsmen and engineers. Despite ever increasing levels of manufacturing automation, a submarine hull relies heavily upon

trained operators making the correct alignment decisions and in-process adjustments to mitigate the impact of variation. The learning curve in hull fabrication from the first submarine hull in a current class of ships to the third has been proven substantial for QP[16]. Through the ongoing accuracy control practices, variation is being addressed in a more effective manner. This assertion in no way implies that the first production unit was of a lower quality or contained a higher variation from nominal. Rather it suggests that the prior production efforts took more resources to control the variation within the process.

Through an aggressive management supported accuracy control effort at QP, the high leverage points have been determined and process changes enacted. The mitigation of variation down to the individual component level allows more precise control over the numerous frame webs and flanges, as well as the shell components. As discussed above, this results in more uniform "kits" for assembly in the frame and shell fixtures. Good frames and shells stem from good components AND good operator interface.

One of the variation mitigation goals of the evolving accuracy control program is to *cut once right* versus *cut to fit*. In other words, if the variation can be controlled within the process capabilities of the burning and shaping equipment, then this would remove the need to cut approximate web arc lengths and chords, etc. This would eliminate the secondary measurement, marking, burning, beveling, and alignment evolutions when the frame kits are erected in the frame fixture. Strides in this direction were being made at the time of this research and the resulting benefits will be closely monitored to evaluate the impact of improved process capability on achieving this stated goal.

Another way to gain insight into the technique of VRM identification, assessment, and mitigation is to turn towards the experience gained in using Key Characteristics

[16] The learning curve effect is documented with data but not quantified here for proprietary concerns.

by other industries. A comparison with higher volume industries is intended to add scope to the QP efforts. The following section presents an overview of the fuselage fabrication process used by Boeing.

4.0 Industry Practices Comparison: Boeing 777 and 767 Aircraft

4.1 Overview and Discussion

The similarities between the fabrication issues for a submarine hull and a modern aircraft fuselage were believed to be much more related than a first observation would suggest. To test this hypothesis, once the QP research and analysis phase of this research was completed, a plant trip to Boeing's 777 and 767 aircraft production facilities was conducted. The purpose of the plant visit was purely qualitative in focus and no VRM analysis is presented here. The goal was to share non-proprietary information about the two industries and the KC methods employed to control the impact of variation.

Compared to Quonset Point's submarine production rate of less than one ship per year, Boeing's approximately four planes per month is a high volume manufacturing plant. Ironically, prior work with benchmarking KC utilization and effectiveness classified Boeing as a low volume producer, along with Lockheed Martin, Allied signal, Textron, ITT, as compared to high volume producers—Ford, GM, Chrysler, and Eastman Kodak [Ertan 1998].

Ertan's work showed that both high and low volume producers experienced similar VRM KC practices but at varying levels of KC Maturity. The strength of this observation lies in the potential learning benefits available to the low volume producer if it were to enact high volume industry practices as a benchmark against their own performance. The study further recognized the potential resource constraints experienced on a per finished product margin for the low volume

producers, but emphasized the importance of a methodical KC identification. Ertan further argues that the high volume producers require more emphasis on KC assessment [Ertan 1998]. Though these observations are clearly desirable in both cases, the author believes that the importance of the mitigation phase of the KC method was under-emphasized. Identification and assessment fall short of providing the cost savings or avoidance benefits that mitigation provides. Going further, identification and assessment, by their nature, require resources while mitigation poses the opportunity to realize a return on those resources. Boeing's efforts have demonstrated the benefits of variation mitigation.

Boeing has been making the transition from fixing the in-process issues to preventing the design-production interface from ever becoming a problem. In VRM terms, Boeing has moved beyond variation *identification* and *assessment* and has enacted actual design and process changes as part of their variation risk *mitigation* scheme.

4.2 Boeing and Quonset Point Similarities and Differences

The fuselage sections of Boeing's large aircraft—the 777 and 767 models—are substantially similar to the ring stiffened submarine hull assemblies shown in Figure 18. In an effort to relate the Boeing terminology to that presented above for QP, some of the processes and nomenclature are the author's and not that employed by Boeing. Aside from material differences—aluminum for aircraft and steel for submarines—the general geometry of a ring stiffened cylinder holds. Figure 25 is an abbreviated Boeing equivalent of the QP submarine hull components diagram presented in Figure 8.

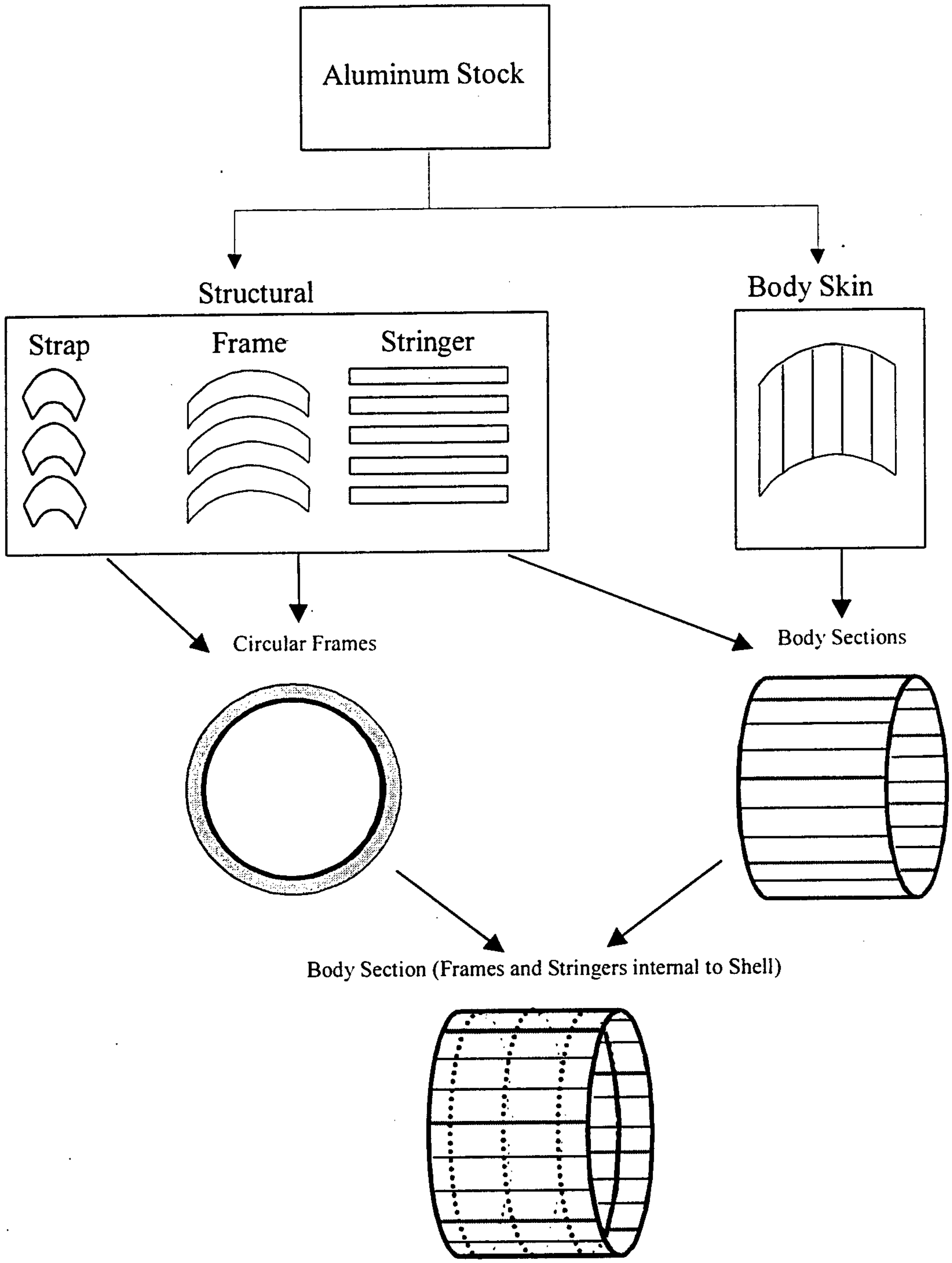

Figure 25: Aircraft Fuselage Components

In this figure, the fuselage cylindrical panels are fabricated in a similar manner as submarine shell assemblies. In addition to the internal circular frames for strength in the submarine, aircraft have longitudinal stiffeners called stringers. For the 777, curved panels are first outfitted with the stringers and other structural elements before being joined into cylindrical shells. In QP's case, the shells are first joined without any other elements attached. The reason for the difference is partly explained by the materials involved and partly by the process. For QP, the shells are relatively thick high-tensile steel and they generally hold their shape once formed. The individual shell components can be moved and fixtured at QP without any other structural elements.

For Boeing, the shell (i.e., the skin of the fuselage) is much more pliable and cannot hold its shape once formed. Boeing uses more tooling to affix longitudinal and circumferencial supports before attempting to join multiple shell panels together. Table 5 provides a pair wise comparison summary of this aspect of the QP and Boeing processes. The table also shows comparisons in the areas discussed in the ensuing paragraphs.

Table 5: Summary of Boeing and Quonset Point Process Comparison

Basis for Comparison	**Boeing Process**	**QP Process**
Cylinder Shell	Panel sections have structural elements attached before assembly into cylinders	Shell plates joined into cylinder before structural elements (i.e., frames) are attached
Section Joins	Longitudinal stringers must be aligned	No longitudinal stiffeners used
	Seat track alignment is a KC	Layout lines are used as a reference for alignment
	Skin gap and fair critical but tooling forces used to align is limited	Gaps reduced with fixture hydraulics forcing alignment
	Keel beam alignment is a KC for longitudinal alignment	Ring reference lines and physical markings used for longitudinal alignment
Trimming	Trim to tool	Trim to part
	Quality controlled by tooling settings	Relies on in-process adjustments to control quality
	Does not limit other process evolutions while being performed	Can become a path limitation evolution

In addition to relatively similar geometric constraints as the ring stiffened submarine hulls, aircraft stringer alignment adds another degree of process control that must be considered, see Figure 26. The alignment of the stringers is a critical portion of the body to body joining process of the fuselage. This is one the critical portions of fuselage assembly and great care is taken to control the positioning of the body sections, skin gap and fair, the stiffener alignment, and the seat track alignment. The later is a parameter used by Boeing for tolerance and manufacturing control to maintain alignment between various body sections. The concept could be extended to QP's practices of maintaining various layout lines for the different hull sections.

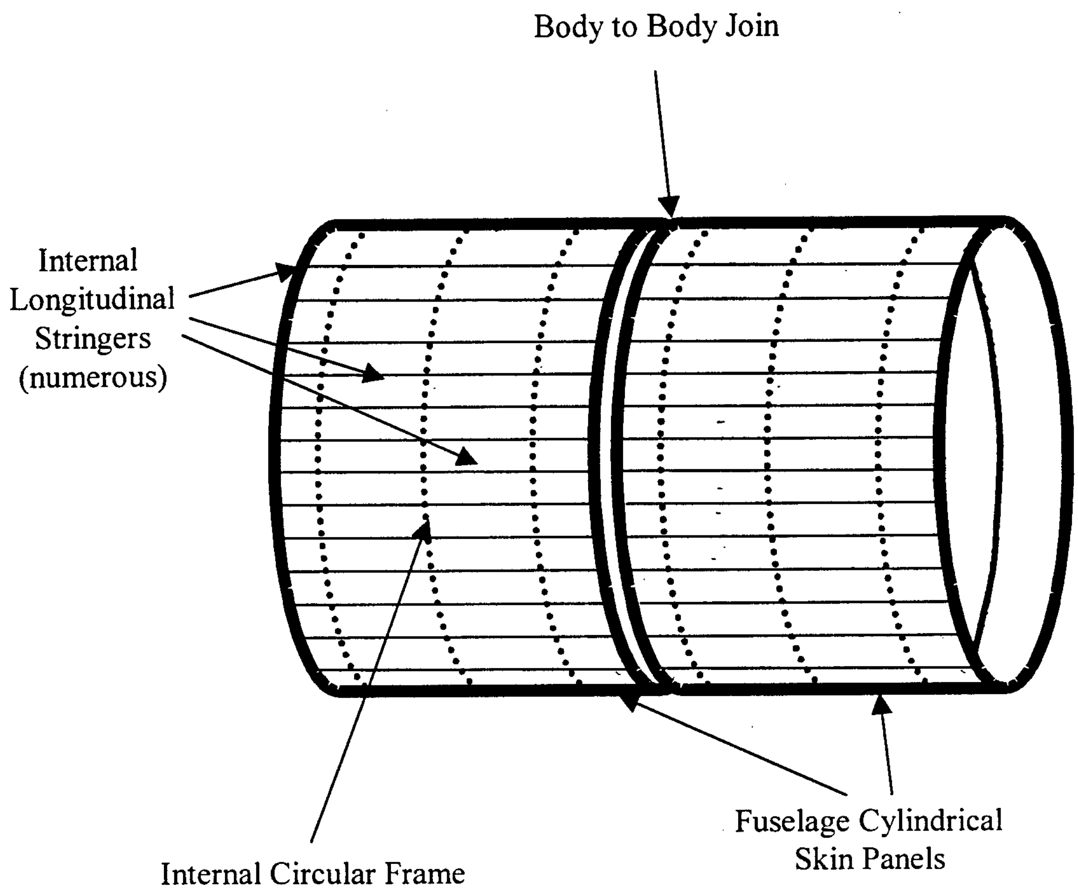

Figure 26: Completed Hull Section

Another interesting comparison between Boeing and QP is their method of maintaining quality in the finished products. In the QP case, the frame subassemblies require a trimming process before the frame assembly is completed, refer to Figure 11. By trimming at the product level, the assembly sequence requires all other frame elements to be in the fixture, tack welded, and ready for assembly. This means that a successful trimming operation will satisfy individual component level quality control, but does not address the subsequent fabrication operations when multiple frames and shells are assembled into rings and sections. The trimming operation at Boeing is at the tool level where the fuselage sections are loaded into the fixture against a hard datum reference at one end, then assembled, and finally have the excess

length/variation trimmed from the other end of the completed section. By trimming to the tool, the production process continues for other fuselage sections without relying upon any particular section as the critical path. The resulting process differences mean that QP maintains quality by adding labor content in the form of in-process adjustments and trimming. Boeing targets quality control by trimming only in the body section level and trying to optimize the previous performance characteristics. When variation results, Boeing adjusts the final body join alignment to reduce the variation.

4.3 Implications of the Comparison

Had this research been the first comparison of the Quonset Point and Boeing processes and methods of addressing variation control, then a more detailed discussion would be warranted. During the plant visit at Boeing, however, it was learned that both companies are engaged in a mutual exchange of process capability and fabrication practices. As such, if and when such work is published, it would provide a much more thorough discussion than this narrowly scoped case comparison was intended to discover.

5.0 Conclusions and Recommendations

5.1 Benefits and Limitations to the KC Method

Though this research lacks enough data fidelity to recommend specific VRM suggestions for the QP process, it does identify that the current direction of the accuracy control group's efforts are on the right path. The KC methodology is very effective in establishing the framework from which to implement a methodical approach to variation control. The three phases of variation risk management—*identification*, *assessment*, and *mitigation* are all reasonably qualified with a KC method. The limitation of the KC flowdown approach lies in the large commitment to learning how to perform the flowdown analysis. By identifying every potential process, part, sub-system, or product features as a Key becomes rapidly cumbersome and inefficient. The true utility for the method comes with considerable experience and the ability to capture only the essential Keys.

The current KC flowdown methods call for a complete tracing of the variation impacts across the entire system. The top-down method requires starting with the final product features and tracing down towards the processes. In the bottom-up method, the part and process variation impacts are flowed upwards towards the final product. Both methods are well suited to specific purposes. The former is most effective in new product development programs where the design team can work with manufacturing engineers to develop a design that is consistent with existing manufacturing process capability. When the design is already in the field, however, the bottom-up approach is more realistic since dramatic changes to the existing production processes can be prohibitively costly.

The Process-to-and-from-Design (PTFD) flowdown method presented here attempts to balance the merits and limitations of both top-down and bottom-up KC flowdown methods. In the *process-to-design* flow, the engineers can identify potential variation control problems within the existing process and communicate this information up to the designers. Only the most significant characteristics are identified. If further efforts call for more variation reduction, then the process can be repeated for more detailed and costly investigations. At the same time, the *process-from-design* flow captures the product KCs and attempts to determine the potentially adverse impact prior processes and subassemblies have on the final product. In this way too, only the more pressing variation contributors are identified. When the results of both methods are reviewed, there will most likely be common elements in either process or design that could be called the Keys to reducing variation. This technique is believed to be less cumbersome than the full top-down or bottom-up flowdown method and allows a company to learn rapidly how to apply the methodology to their system. As the flowdown experience reaches deeper into the organization, the KC method begins to take hold and then allows more detailed variation reduction efforts with less resource costs.

5.2 Recommendations for Follow-on Effort

The data analysis of the Quonset Point procedures for modular submarine hull fabrication suggests that there are some very realizable benefits to implementing the KC method into the current accuracy control practices. Though the data set was poorly populated, there appears to be an observable trend that the technicians on the floor recognize. By spending the extra effort on providing good parts—that is low variation from nominal—and extra effort in the initial fixturing processes, the resulting downstream effects are dramatic. By performing the analyses discussed

herein, a better labor content target could be set which allows the operators to begin the fabrication sequence on a strong foundation and flow the reduced variation up from the processes towards the final product. Further data collection and analysis would support this assertion and identify the actual hull to hull learning curve within the Automated Frame and Cylinder Fabrication facility (AFC). In addition, the increased data may provide the much desired quantifiable quality loss information including asymmetric variation content.

Further work in this area would include the use of electronic data collection on the essential variation areas versus the collection of multiple in-process checks and validations. The later is completely necessary until the variation is brought under more quantifiable control. To begin further exploration, the author recommends that QP charter an in-depth study which applies the PTFD KC method to a more complete data set. This would increase the statistical significance of the trends presented here. Since the small data sample did in fact identify, albeit weakly, the expected results based on operator interviews and experience, the added significance brought with more data would be a necessary first step. This can then begin the mathematical formulation for the systematic understanding of accuracy control risk. It could show the high leverage areas where additional labor or facilities infrastructure outlays are warranted because they result in downstream quality and cost savings. Applied to modular submarine hull fabrication processes presented herein, further analysis would provide the necessary information to make ROI decisions on the control of variation.

5.3 Closing Remarks

Aside from the data, the KC methodology, and the analysis of this research, one factor remains essential for the success of delivering quality submarines to the U.S. Navy—people. Production technicians, engineers, and equipment operators have been and will continue to be an essential part of a successful submarine production

program. In recognizing this, variation risk management becomes more than a purely quantifiable numbers game. Inclusion of the personnel factor, coupled with sound engineering design and product development initiatives can benefit from the KC PTFD method and provide sweeping returns to our Navy and our country.

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